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RESEARCH REPORT

RP 213

Performance Evaluation of Asphalt Pavement Mixes in Idaho that Contain High Percentages of Recycled Asphalt Pavement

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16. Abstract

Currently, Idaho Transportation Department (ITD) allows the use of high percentages of reclaimed asphalt pavement (RAP) in an asphalt mix after virgin binder grade is adjusted. However, it is imperative to ensure that RAP mixes can perform at least as well as virgin mixes. In response to this need, this study examined 2 classes of asphalt mixes (SP4 and SP5), which included a total of 10 mix designs with different percentages of RAP from 2 sources. The researchers evaluated mixes' laboratory performance as well as AASHTOWare Pavement ME Design field performance predictions in terms of resistance to rutting, fatigue cracking, and low temperature thermal cracking. Generally, even after binder grade adjustment, the rutting resistance of RAP mixes increased with an increase in RAP percentage, indicating that the current practice of binder adjustment cannot account for the stiffening effect of RAP. The fatigue cracking resistance of the mixtures with a low percentage (i.e., 17 percent) of RAP was comparable to that of the virgin mix. However, the effects of high percentage RAP (more than 17 percent) on fatigue cracking depended on target PG of virgin binder. When the virgin binder is not polymer modified (e.g. PG 58-28), bumping down the grade of virgin binder did not affect the fatigue resistance of high RAP mixes, such as the case of North Idaho mixes. However, when the virgin binder is polymer modified (e.g. PG 70-28), bumping down the grade of virgin binder may lead to elimination or reduction of the degree of polymer modification which affects the fatigue resistance of high RAP mixes, such as the case of South Idaho mixes. The addition of RAP (either a low or high percentage) could adversely affect the thermal cracking resistance of RAP mixtures. The mixture's volumetrics also affect the performance. The researchers recommend that a performance test for cracking should be included in the mix design; specifically, AASHTO T283-14, which can help determine both the moisture susceptibility and cracking performance of a mixture (i.e., indirect tensile fracture work density), should replace the current ITD moisture susceptibility test. The research team also recommends that fracture criteria for asphalt mixes should be developed by coring in-service pavements that exhibit both good and bad performance. Alternatively, empirical models and procedures were developed to design RAP mix without conducting performance tests which is worth validation in future study.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
Note: Volumes greater than 1000 L shall be shown in m^3				
		TEMPERATURE (exact)		
^{o}F	Fahrenheit temperature	5/9 (^{o}F-32)	Celsius temperature	^{o}C
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb
mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
^{o}C	Celsius temperature	9/5 ^{o}C+32	Fahrenheit temperature	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

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List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AMPT	Asphalt Mixture Pavement Analyzer
ANOVA	Analysis of Variance
APA	Asphalt Pavement Analyzer
BBR	Beam Bending Rheometer
COV	Coefficient of Variation
DSR	Dynamic Shear Rheometer
ESALs	Equivalent Single Axle Loads
FWD	Fracture Work Density
GS	Gyratory Stability
HMA	Hot Mix Asphalt
IDT	Indirect Tensile
IRI	International Roughness Index
ITD	Idaho Transportation Department
MEPDG	Mechanistic-Empirical Pavement Design Guide
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size
PAV	Pressure Aging Vessel
PG	Performance Grade
RAP	Recycled Asphalt Pavement/Reclaimed Asphalt Pavement
RTFO	Rolling Thin-Film Oven
STD	Standard Deviation
SGC	Servopac Gyratory Compactor
TSR	Tensile Strength Ratio
TSRST	Thermal Stress-Restrained Specimen Test
WMA	Warm Mix Asphalt
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate

Executive Summary

Introduction

The use of recycled asphalt pavement (RAP) in hot mix asphalt (HMA) or warm mix asphalt (WMA) is potentially beneficial to both the environment and the economy. Virgin aggregate and asphalt binders can be conserved to reduce construction costs, energy consumption, and greenhouse gas emissions. Currently, Idaho Transportation Department (ITD) allows use of RAP in asphalt mixes. The amount of RAP that a contractor may use depends on the source of RAP, fractionation of RAP, and the "lift" of the pavement at which RAP is used.(1)

Because the aged binder in RAP can cause mixes to become brittle, which results in less resistance to cracking when the mix design calls for a high percentage of RAP binder in an asphalt mix, pavement engineers often adjust the performance grade (PG) of the virgin binder to compensate for this stiffening effect of the aged RAP binder. According to current ITD standard specifications, when RAP binder replacement ratio in the asphalt mix is less than 17 percent, no binder grade adjustment is needed. If RAP binder replacement ratio is between 17 percent and 30 percent, the virgin binder shall be 1 grade lower for the high and low temperatures designated. When RAP binder replacement ratio is higher than 30 percent, designers use a blending chart to select the grade of virgin binder, based on the assumption that the grade of the blended binder is proportional to RAP binder percentage and the assumption that RAP binder and virgin binder are blended together thoroughly.

However, the assumption of complete blending might not always be reasonable for a RAP mixture when a high percentage of RAP is used in the asphalt mix, even if designers have "bumped" the asphalt binder grade and followed a blending chart. Therefore, researchers must address the possible effects of RAP binder and virgin binder selection on the performance of the asphaltic materials and pavement, especially the performance in terms of cracking. Also, investigation is need on the predicted field performance of asphalt mixes that contain high percentages of RAP binder under actual traffic and climate conditions. Therefore, the objectives of this research project are to:

1. Evaluate the effects of various percentages of RAP on mix designs, laboratory performance, and predicted field pavement performance in terms of resistance to rutting, fatigue cracking, and thermal cracking.
2. Make recommendations that ITD could consider for updating its current RAP specifications to improve asphalt pavement performance.

Research Methodology

This study evaluated a total of 10 mixes, including 8 laboratory-produced mixes and 2 plant-produced mixes. The research team characterized two types of RAP materials, referred to as North RAP from Northern Idaho, and South RAP from Southern Idaho, in terms of binder content, RAP aggregate gradation, bulk specific gravity (G_{sb}) of RAP aggregate, and PG of the extracted and recovered RAP binders. Two plant mixes, the North field mix with 30 percent RAP (referred to as NF30) and the South field mix with 26 percent RAP (referred to as SF26), served as the reference mixes for the laboratory mix design of North mixes with 0, 17, 30, and 50 percent RAP (referred to as N0, N17, N30, N50) and South mixes with 0, 17, 26, and 50 percent RAP (referred to as S0, S17, S26, S50), respectively. The gradations for the laboratory-produced North and South mixes were the same as those for the plant-produced North and South mixes. The virgin binder selection for each mix was based on ITD specifications and the binders that were available in the local market. For the North mixes, PG of the virgin binder used in N0 and N17 was PG 58-28, and PG of the virgin binder used in N30, N50, and NF30 was PG 52-34. For the South mixes, PG of the virgin binder used in S0 and S17 was PG 70-28, PG of the virgin binder used in S26 and SF26 was PG 64-34, and that used in S50 was PG 58-34. The research team determined the optimum binder content for each mix and determined the volumetric properties, such as voids in mineral aggregate (VMA) and voids filled with asphalt (VFA).

The research team evaluated the laboratory performance of the North and South mixes that contained different percentages of RAP in terms of rutting resistance, fatigue cracking resistance, and low temperature thermal cracking resistance. The research team conducted flow number and gyratory stability tests to determine the stability and resistance to rutting of the asphalt mixes containing different percentages of RAP**.** The research team also conducted indirect tensile (IDT) tests at 68°F to investigate the mixes' resistance to fatigue cracking. The research team used fracture work density and vertical failure deformation values obtained from IDT tests to characterize the mixtures' resistance to bottom-up fatigue cracking and top-down fatigue cracking, respectively. Similarly, the research team used the fracture work density values obtained from IDT tests at 14°F to evaluate the mixtures' resistance to low temperature thermal cracking.

The research team also conducted mechanistic-empirical analysis by using AASHTOWare Pavement ME Design software. The research team collected and determined the inputs, which included pavement structure, climate, traffic data, and material properties. The average annual daily truck traffic (AADTT) values were based on traffic volumes predicted by ITD. The research team employed nationally-calibrated distress models. The research team compared all the predicted pavement distress values at 90 percent reliability over a pavement design life of 20 years.

Key Findings

Based on the test results from this research project, the key findings are as follows:

- The laboratory performance evaluation showed that resistance to rutting due to lateral shear failure, as indicated by the flow number, increased as RAP percentage increased. It also indicated that the current practice of binder grade adjustment cannot account for the stiffening effect of RAP, and indicated that the blending of RAP binder and virgin binder may not be thorough or complete. The aggregate structural stability of RAP mixtures, as indicated by the gyratory stability test results, was comparable to or slightly better than that of the control mix. Overall, RAP mixes performed the same as or better than the control mix in terms of rutting resistance.

- The fatigue cracking resistance of mixtures with a low percentage (i.e., 17 percent) of RAP was comparable to that of the virgin mix. However, the effects of high percentage of RAP (more than 17 percent) on fatigue cracking depended on the target PG of virgin binder. When the target virgin binder is not polymer modified (e.g. PG 58-28), bumping down the grade of virgin binder did not affect the fatigue resistance of high RAP mixes, such as the case of North Idaho mixes. However, when the virgin binder is polymer modified (e.g. PG 70-28), bumping down the grade of virgin binder may lead to elimination or reduction of the degree of polymer modification which affects the fatigue resistance of high RAP mixes, such as the case of South Idaho mixes.

- The addition of RAP (either a low or high percentage) could adversely affect the thermal cracking resistance of RAP mixtures.

- When the virgin binder grade, determined according to the blending chart, was too low to be available in the market or was too costly, the use of a higher grade did not seem to compromise the material's performance. The high temperature target PG is preferred to avoid the loss of or reduced use of polymer in virgin binder.

- The AASHTOWare Pavement ME Design predictions for the performance of pavements that contained different RAP percentages followed the trend of the laboratory properties, because the performance models within the AASHTOWare Pavement ME Design software also utilize these properties.

Recommendations for Implementation

- It is recommended that the high temperature PG of target binder is kept regardless of RAP percentage, without bumping down, to ensure the polymerization of the virgin binder, if any, and thus good fatigue performance of RAP mixes.

- The research team recommends that the current ITD test method for evaluating moisture susceptibility, which is based on unconfined compressive strength testing, be changed to the method found in *AASHTO T283-14, Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage*,(2) which is based on IDT test. The testing of unconditioned IDT specimens in AASHTO T283-14 also provides parameters (e.g., fracture work density and vertical failure deformation) to assess the cracking performance of a mix. A cracking criterion for a mix can be established by testing the cores from in-service pavements with and without cracking.

- Alternatively, if it is difficult to include a cracking performance test in a mix design, the empirical model to determine the low temperature grade of virgin binder for RAP mix is recommended to use instead of the grade bumping and blending chart. This empirical model will require further validation. The developed procedures for virgin binder selection are as follows:

  1. Design a control mix without RAP to meet ITD specification with a binder of target PG.

  2. Estimate fracture work density of control mix at low temperature ($FWD_{low\_control}$) based on the equation shown in Figure 1:

$$FWD_{low\_control}=9.437+0.179P_{RAP}-5.209AV+6.690VMA_{control}+1.475PG_{target\_low}-0.513PG_{target\_high}$$

where:

$FWD_{low\_control}$ = Fracture work density of control mix at low temperature, psi.
P_{RAP} = Percentage of RAP, percent; 0 percent in this case.
AV = Design air void, 4 percent in most cases.
$VMA_{control}$ = Void in mineral aggregate of control mix, percent.
PG_{target_low} = Low temperature grade of target binder.
PG_{target_high} = High temperature grade of target binder.

Figure 1. Prediction of Fracture Work Density of Control Mix at Low Temperature

3. Design RAP mix to meet ITD specification with a binder of PG_{virgin_high} and any low temperature PG, because the low temperature PG of binder does not significantly affect the volumetrics of a mix. Keep the high temperature PG of target binder for RAP mix. The benefit of using high temperature PG of target binder for RAP mix is to avoid change of use of polymer modified binder, if any, to unmodified binder if softer virgin binder was selected and the rutting performance is ensured.

4. Determine the low temperature PG of virgin binder for RAP mix using the equation as Figure 2, based on RAP mix's design air void, VMA, P_{RAP}, $FWD_{low\_control}$, and PG_{virgin_high}

$$PG_{virgin\_low}=(FWD_{low\_control}-9.437-0.179P_{RAP}+5.209AV-6.690VMA_{RAP}+0.513PG_{virgin\_high})/1.475$$

where:

$FWD_{low\_control}$ = Fracture work density of control mix at low temperature from Step 2, psi.
P_{RAP} = Percentage of RAP, percent.
AV = Design air void, 4 percent in most cases.
VMA_{RAP} = Void in mineral aggregate of RAP mix, percent.
PG_{virgin_low} = Low temperature grade of virgin binder.
PG_{virgin_high} = High temperature grade of virgin binder.

Figure 2. Virgin Binder Selection of Low Performance Grade for RAP Mixes

Recommendations for Further Study

- A cracking criterion of performance test for mix design is recommended to be developed.
- The empirical model and corresponding RAP mix design method developed in this study is recommended to be validated**,** with more RAP mixes, especially with plant mixes and/or field performance.

- This study focused on the effects of RAP in HMA. The South plant-produced mix was a WMA mix. However, because the research team reheated this foaming WMA mix in the laboratory before compaction, WMA mix was actually a HMA mix. The effects of RAP on WMA could be different from the effects on HMA, because the relatively lower mixing temperature used for WMA mixes could complicate certain factors, such as the thoroughness of the blending process. Therefore, the research team recommends further study of the effects of high RAP percentages on WMA mixes.

Chapter 1
Introduction

Background and Problem Statement

The use of recycled asphalt pavement (RAP) in asphalt mixes is potentially beneficial to both environment and economy. Virgin aggregate and asphalt binder can be conserved to reduce construction costs, energy consumption, and greenhouse gas emissions. The economic benefits of using 20 to 50 percent RAP in the mix could result in 14 to 34 percent cost savings per ton of asphalt mix.(3) Currently, Idaho Transportation Department (ITD) allows the use of RAP in asphalt mixes for pavement construction and rehabilitation projects. The amount of RAP that a contractor may use depends on RAP category, RAP processing, and the lift of the pavement for which RAP is intended.(1) Category 1 RAP is defined as being from or traceable to an agency project; thus, RAP quality can be assured without extensive aggregate testing. If Category 1 RAP is processed by crushing and screening to a consistent gradation and binder content, it can be used in any lift (top or lower) of the asphalt pavement at any RAP binder replacement percentage, namely up to 100 percent RAP by weight of the total binder of the mixture. If Category 1 RAP is not processed, it is limited to 17 percent maximum in the top lift and to 30 percent maximum in a lower lift. RAP materials that are not from or traceable to an ITD project are defined as Category 2 RAP. If Category 2 RAP is processed, it is allowed up to 10 percent in the top lift and limited to 30 percent maximum in a lower lift. Category 2 RAP that is not processed is not allowed in the top lift and is limited to 17 percent maximum in a lower lift. However, a Category 2 RAP can be considered as a Category 1 RAP if the contractor tests the Category 2 RAP for aggregate quality and the properties of the Category 2 RAP components meet the specifications for virgin materials.(1)

Generally, aged binder that is present in RAP increases the stiffness of the mixture and the mixture's resistance to rutting.(4,5,6,7,8,9,10) However, the aged binder in RAP can also cause brittleness of the mixture and make it susceptible to cracking, such as fatigue cracking or thermal cracking, especially when a high percentage of RAP binder is used in the hot mix asphalt (HMA).(4,5,11,12) In order to compensate for the stiffening effect of aged RAP binder, it is often necessary to adjust the performance grade (PG) of the virgin binder based on RAP binder replacement ratio. According to ITD standard specifications, when RAP binder replacement ratio for HMA is less than 17 percent, no binder grade adjustment is needed.(1) If RAP binder replacement ratio is between 17 and 30 percent, the grade of the virgin binder shall be one grade lower for the high and low PG temperatures designated.(1) When RAP binder replacement ratio is higher than 30 percent, designers use a blending chart to select the grade of the virgin binder, based on the assumptions that the grade of the blended binder is proportional to RAP binder percentage and that the blending between RAP binder and virgin binder is complete.

However, the assumption of complete blending of RAP binder and virgin binder might not always be reasonable for RAP mixtures.(13,14,15) Therefore, the effects of RAP binder and virgin binder selection on the performance of asphaltic materials and pavement performance require further investigation. Also, agencies, including ITD, currently specify mix designs for contractors to follow without concern over the mechanical performance of asphalt mixes that contain RAP, except for moisture susceptibility and sometimes rutting. Therefore, it is imperative to study the effects of RAP binder and virgin binder grade selection to ensure that the performance of an asphalt mix that contains RAP is not compromised.

Objectives

The overall goal of this study is to assess the effects of RAP on the performance of asphalt pavements. Specific objectives of the project are to:

1. Evaluate the effects of different percentages of RAP on mix designs, laboratory performance, and predicted field pavement performance in terms of resistance to rutting, fatigue cracking, and thermal cracking in the laboratory.

2. Make recommendations that ITD could consider for updating its current RAP specifications to improve asphalt pavement performance.

Report Organization

This report is organized in six chapters, followed by three appendices, as follows:

Chapter 1 provides the introduction to this research project, presents the problem statement regarding RAP usage in asphalt mixes, and states the research objectives.

Chapter 2 presents a literature review of RAP characterization, mix design, and laboratory and field performance information for mixes that contain RAP materials.

Chapter 3 presents the laboratory test methods and results for RAP characterization and mix designs for asphalt mixes with different percentages of RAP.

Chapter 4 presents the laboratory test methods and results for the laboratory performance of asphalt mixes with different percentages of RAP in terms of the mixtures' resistance to rutting, fatigue cracking, and thermal cracking.

Chapter 5 presents the results and analysis of the field performance predictions obtained using AASHTOWare Pavement ME Design software for RAP mixes.

Chapter 6 summarizes the key findings from this research and presents recommendations for ITD's consideration.

Appendices A, B and C provide mix design results, laboratory performance test results, and inputs information for AASHTOWare Pavement ME Design, respectively.

Chapter 2
Literature Review

This chapter presents a literature review of relevant studies of RAP in asphalt mixes and the subsequent effects on pavement performance. The topics reviewed include methods for RAP characterization, mix designs for mixes containing RAP, laboratory performance, and the field performance of mixes containing high RAP contents.

RAP Characterization

In order to incorporate RAP materials into asphalt mixes, RAP must be characterized in terms of binder content, aggregate gradation, aggregate quality, bulk specific gravity (G_{sb}) of RAP aggregate, and PG of the recovered RAP binder if blending chart is used.

Generally, the methods used to extract RAP aggregate and to determine RAP binder content and RAP aggregate gradation include the ignition oven method according to *AASHTO T308-10*, *Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix Asphalt (HMA) by the Ignition Method*, the solvent extraction and recovery method according to *AASHTO T164-14*, *Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)*, and *AASHTO T319-14*, *Standard Method of Test for Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*.(16,17,18) McDaniel et al. in 2001 and Hajj et al. in 2012 investigated the impacts of these extraction methods used to determine binder content and RAP aggregate gradation.(4,19) Their results showed that the RAP binder content, as determined by the ignition oven method without considering correction factors, was close to the true binder content of laboratory-simulated RAP materials, whereas the binder content determined from the solvent extraction method was lower than the true value because the solvent could not remove all the aged binder from RAP.(4,19) Neither of the extraction methods had a significant impact on the gradation change of the coarse aggregate portion, whereas the change in the fine aggregate gradation, based on the ignition oven results, depended on the aggregate source; that is, some types of aggregate either broke down or were lost when subjected to the extreme temperatures in the ignition oven.

The bulk specific gravity of RAP aggregate is another critical property to consider for mix designs with RAP. Studies show that a small error in the bulk specific gravity value can result in the voids in mineral aggregate (VMA)value being off by ± 0.4 percent as RAP content approaches 50 percent.(19,20) Currently, three methods are available to determine the bulk specific gravity of RAP aggregate:

- The first one is an extraction method, using either solvent or an ignition oven, to produce relatively clean aggregate particles and then to determine the bulk specific gravity of the extracted coarse and fine aggregate using *AASHTO T85-14, Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate*, and *AASHTO T84-13, Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate*, respectively.(21,22) Prowell et al. in 2000 and Hajj et al. in 2012 studied the effects of both the solvent extraction and ignition oven extraction methods on the changes of specific gravity.(19,23) The solvent extraction method seemed to have less effect on the measurement of the bulk specific gravity of RAP aggregate than the ignition oven method.(19,23) However, both extraction methods were likely to cause small errors in the bulk specific gravity values of RAP aggregate.(23)

- The second method, referred to as the indirect or back-calculation method, uses the effective specific gravity (G_{se}) of RAP aggregate instead of the bulk specific gravity in the calculation of VMA. However, researchers strongly recommend not to use the effective specific gravity in the calculation of VMA, because this practice can cause a significantly inaccurate VMA value.(19,23)

- The third method is also an indirect approach that is based on maximum specific gravity (G_{mm}) testing and the assumption of asphalt absorption in RAP. Practicing engineers can use this approach, but only if they could estimate the asphalt absorption confidently.(11,19)

The blending chart used for virgin binder selection indicates that PG of recovered RAP binder should be determined when RAP content exceeds 25 or 30 percent according to *AASHTO M323-13 Standard Specification for Superpave Volumetric Mix Design* or ITD specifications, respectively.(1,24) NCHRP Report 452 proposed detailed procedures for determining PG of recovered RAP binder and recommended only rolling thin-film oven (RTFO) aging before testing.(4) This simplification has significantly reduced the amount of recovered RAP binder needed and the time required to grade RAP binder.(11)

In summary, both the ignition oven and solvent extraction methods can be used to determine the binder content and gradation of RAP aggregate. However, care should be taken when ignition oven method is used, if the type of RAP aggregate is likely to break down or burn away under the temperature necessary to burn off binder in the ignition oven. Also, it is important to determine the bulk specific gravity of RAP aggregate precisely, because even a small error will amplify the error in VMA calculation. The each of three current methods for determining bulk specific gravity has its own merits and drawbacks.

Mix Design

Currently, most state transportation departments use the Superpave mix design method for mixes that contain RAP materials.(25) The challenges of mix design that can arise from the use of RAP include the following considerations:

- Variability of RAP materials.

- Selection of the appropriate amount of RAP to use in the mixture and the selection of the appropriate virgin binder to compensate for the stiffening effect of the aged RAP binder based on RAP percentage.

- Effects of RAP on the mixture’s moisture susceptibility.

The variability of the binder content and gradation of RAP materials, which possibly stems from the combination of multiple layers of materials in one project or RAP from several projects in a single stockpile, can make it difficult for the contractor to meet the mix design specifications and limit the amount of RAP used in the mixture.(4, 26,27) Significant variations in the binder content of RAP materials can result in significant variations in the binder content of the plant mix. For example, one study showed that projects with high percentages of RAP had higher levels of variability than a typical HMA project without RAP.(28) However, recently-developed practices for managing RAP stockpiles and processing RAP materials have helped to control RAP variability.(11,27,29,30) These best practices include fractionation, avoiding contamination by keeping deleterious materials out of RAP stockpiles, not over-crushing RAP, ceasing processing during rain, and minimizing moisture in RAP stockpile by covering it, etc. Details of these practices are available in Appendix D of NCHRP Report 752.(11) A survey conducted by National Center for Asphalt Technology from 2007 to 2008 indicates that proper management of RAP stockpiles could control RAP variability. The survey showed that the standard deviations of the binder content in RAP stockpiles ranged from 0.1 to 1.5 percent, and the standard deviations of the percentages passing the median sieve and 75 micron sieve ranged from 0.78 to 9.0 percent and 0.3 to 3.0 percent, respectively.(31) Also, RAP stockpiles could possibly be even less variable than virgin aggregate.(32,33)

In addition to considering RAP variability that can limit the amount of RAP used in asphalt mixes, other factors that limit the maximum amount of RAP that can be incorporated into asphalt mixtures include the availability of RAP, specification limits, properties of RAP binder, availability of specified virgin binder, and the capability of the hot mix plant to handle RAP materials for drying and heating, etc.(34) As mentioned earlier, the fractionation of RAP can reduce the variability in the gradation and binder content of RAP materials. Therefore, any limitations to the use of high percentages of RAP depend mainly on the proper selection of the virgin binder in RAP mixture to compensate for the effect of the aged binder in RAP. Based on NCHRP Report 452,(4) *AASHTO M323-13* provides binder selection guidelines for RAP mixtures.(24) These selection guidelines include that, if RAP percentage is less than 15 percent, there is no need to change the virgin binder grade. For RAP percentages between 15 and 25 percent, the virgin binder shall be 1 grade lower than the targeted performance grade at both the high and low temperatures. For RAP percentages higher than 25 percent, a blending chart is needed for the binder grade selection. Based on the desired final blended binder grade, the desired RAP percentage, and the recovered RAP binder properties, the required properties of the virgin binder grade can be determined as Figure 3:(4)

$$\mathrm{T_{virgin}} = \frac{\mathrm{T_{blend}} - (\%\mathrm{RAP} \times \mathrm{T_{RAP}})}{(1 - \%\mathrm{RAP})}$$

where:

$\mathrm{T_{virgin}}$ = Critical temperature of the virgin asphalt binder.
$\mathrm{T_{blend}}$ = Critical temperature of the blended asphalt binder.
%RAP = Percentage of RAP, percent.
$\mathrm{T_{RAP}}$ = Critical temperature of the recovered RAP binder.

Figure 3. Selection of Critical Temperature of Virgin Asphalt Binder

If the mix design calls for a specific market-available virgin binder, and the desired blended binder grade and recovered RAP properties are known, the percentage of RAP that can be used in the mixture is determined as Figure 4:(4)

$$\%\mathrm{RAP} = \frac{\mathrm{T_{blend}} - \mathrm{T_{virgin}}}{\mathrm{T_{RAP}} - \mathrm{T_{virgin}}}$$

Figure 4. Selection of Percentage of RAP Used in Mixture

In practice, the use of a blending chart is time-consuming, involves hazardous solvents to extract RAP binder, and creates disposal problems.(25) Furthermore, the assumption that the virgin binder and RAP binder are completely blended may not always be reasonable.(13,14,15) The thoroughness of the blending process can affect the performance of RAP mixes, as poor blending of the virgin binder and RAP binder could compromise the mixture's resistance to rutting, moisture damage or cracking.(13) Therefore, selecting the proper virgin binder for RAP mixtures remains a substantial challenge.

In addition to the requirements for the volumetric properties, another consideration for the mix design is the moisture susceptibility of RAP mixes. *AASHTO T283-14*, *Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage*, provides the commonly-used method for moisture susceptibility evaluation.(2) The tensile strength ratio (TSR) of samples subjected to freeze-thaw and dry conditions is an indicator of HMA's resistance to moisture damage. Overall, studies for moisture susceptibility of RAP mixes show that the addition of RAP to a mixture has no positive or negative impact on the mixture's moisture susceptibility and that most RAP mixes can satisfy the local requirements for a minimum TSR value.(8,12,35) Even though in several cases that NCHRP Report 752 investigated that TSR values of mixes with high RAP percentages were lower than those of the virgin mixes or the criterion of 0.80 requirement in *AASHTO M323-13*, the addition of anti-stripping additives helped improve TSRs above 0.80.(11,24)

In summary, appropriate processing methods, such as fractionation, can effectively reduce RAP variability in terms of binder content and gradation. Therefore, RAP variability should not be a limitation to increase the RAP content in asphalt mixes. However, currently, the proper virgin binder selection process remains a challenge to achieve high RAP percentage mixes that perform comparably with mixes without RAP, due primarily to the complex issue of blending between RAP binder and virgin binder completely. Also, RAP mix designs generally require moisture damage susceptibility tests; these tests' results indicate that the effect of high percentages of RAP on moisture susceptibility is limited and that the addition of anti-stripping additives can help satisfy the criterion for moisture damage resistance. In short, mix designs that include high percentages of RAP are possible and can be designed to meet current specifications.

Laboratory Evaluation of Laboratory-Produced RAP Mixes

The evaluation of laboratory and field performance of asphalt mixtures with RAP is of great importance for selecting the appropriate amounts of RAP to use in the mixtures. Based on a literature review, the evaluation factors used in this study include rutting resistance, fatigue cracking resistance, and low temperature thermal cracking resistance. Therefore, the following sections of this literature review present the evaluation of RAP mixes in terms of rutting resistance, fatigue cracking resistance, low temperature thermal cracking resistance in the laboratory, and for field pavement performance.

Rutting Resistance

Rutting is a common distress in asphalt pavements, particularly in hot climates. The dynamic modulus (E*), which is a mixture stiffness indicator, is a principal material property for predicting rut depth by Mechanistic-Empirical Pavement Design Guide (MEPDG). The flow number (FN) is also a performance indicator for permanent deformation due to shear failure; as the flow number increases, rutting resistance to shear failure increases.(34) Both the dynamic modulus value and flow number can be determined using an Asphalt Mixture Performance Tester (AMPT).

Generally, the dynamic modulus and flow number values are expected to increase with increasing RAP percentages due to the stiff binder in RAP materials. However, a different test temperature, frequency, virgin binder grade, optimum binder content, and/or aggregate gradation could also affect the values of the dynamic modulus and flow number.(6,12,36,37) Li et al. in 2004 tested Minnesota mixes with 0, 20, and 40 percent RAP to study the effects of RAP percentage, virgin binder grade, and RAP sources on the dynamic modulus.(36) They have found that the addition of RAP to the mix increased the dynamic modulus value when compared to the control mix. However, at a low temperature, the modulus value did not always increase with the addition of RAP, likely because of the formation of micro-cracks at the low test temperature, which possibly decreased the stiffness of the mixture.(36) Li et al. found that the virgin binder grade and RAP source had a significant effect on the complex modulus values.(36)

Daniel et al. in 2005 studied the dynamic modulus values of mixes containing 0, 15, 25, and 40 percent RAP.(6) The addition of 15 percent RAP in the mix increased the dynamic modulus value compared with the control mix, whereas the addition of 25 and 40 percent RAP did not follow expectations; that is, the dynamic modulus curves of 25 and 40 percent RAP mixtures were close to that of the control mix. (6) Possible reasons for this unexpected trend are that 25 percent RAP mix had a higher optimum binder content than 15 percent RAP mix, and the gradations for 25 and 40 percent processed RAP mixtures were finer than that of control mix. Both 25 percent RAP mix and 40 percent RAP mix had higher VMA and voids filled with asphalt (VFA) values than those of the control mix and 15 percent RAP mix.(6) These findings indicate that factors other than RAP percentage could significantly affect the properties of mixes containing RAP.

McDaniel et al. in 2012 studied plant mixes with 0, 15, 25, and 40 percent RAP obtained from 5 contractors. The relationship between RAP content and dynamic modulus value did not follow the same trend among the different mixes.(37) Al-Qadi et al. in 2012 studied 2 different mixes from 2 districts with different percentages of RAP and the effect of binder grade bumping (PG 64-22, PG 58-22, and PG 58-28) on the dynamic modulus and flow number.(12) Their results showed that as RAP content increased, the dynamic modulus values and flow numbers increased due to the aged binder in RAP. They also found that bumping-down binder grade could reduce the dynamic modulus value and increase the rutting potential, as indicated by flow number and wheel tracking test results.(12)

In addition to stiffness evaluations using dynamic modulus and flow number tests, the Asphalt Pavement Analyzer (APA) and Hamburg wheel tracking tests can provide a direct evaluation of rutting resistance. Based on these rutting test methods, several studies reached similar conclusions; i.e., mixes that contain RAP perform better than mixes without RAP in terms of rutting resistance.(10,38,39,40,41,42) Putman et al. in 2002 used APA to evaluate the effects of RAP material and crumb rubber-modified (CRM) binder on rutting resistance.(38) Their test results indicated that mixes containing RAP or CRM binder had similar or better rutting resistance than mixes without RAP or with unmodified binder.(38) Colbert et al. in 2012 used APA at 136.4°F to study the rutting resistance of mixes with 0, 15, 35, and 50 percent RAP.(10) Their results showed that as more RAP was added to the mix, the rutting depth decreased, that is the rutting resistance increased.(10) Zhao et al. in 2012 conducted laboratory performance tests to study the effect of high percentages of RAP on warm mix asphalt (WMA) mixtures.(40) Zhao et al. employed the Marshall mix design procedure to produce 4 WMA mixtures with the same aggregate gradation that contained 0, 30, 40, and 50 percent RAP with PG 64-22 virgin binder. This study also used APA at 122°F to conduct rut depth tests. The results showed that resistance to rutting improved by adding RAP to the mixes and that the improvement in WMA mix performance was better than HMA mixes.(40) Other researchers, such as Stroup-Gardiner et al., Vavrik et al., and West et al., came to similar conclusions.(39,41,42)

Fatigue Cracking Resistance

Typical fatigue tests to evaluate a mixture's resistance to fatigue cracking include the bending beam fatigue test, Texas overlay tester test, Indirect Tensile (IDT) fracture energy test, and semi-circular bending test. Most studies that have investigated resistance to cracking concluded that RAP mixtures exhibit a reduced fatigue life or more brittle behavior at high percentages of RAP content, but at low percentages of RAP content (less than 20 percent), the addition of RAP seems to increase fatigue cracking resistance.(4,8,11,43,44) For instance, McDaniel et al. in 2001 used bending beam fatigue tests at 400 and 800 microstrains at 68°F to evaluate the fatigue life of mixtures containing different percentages of RAP (0, 10, 20, and 40 percent) from 3 different sources.(4) Their results showed that the mixtures' stiffness values increased and the fatigue life decreased for higher RAP contents with no adjustment to the virgin binder grade.(4) Kingery in 2004 and Vukosavljevic in 2006 used IDT strength, semi-circular bending, and bending beam fatigue tests to evaluate mixtures containing 0, 10, 20, and 30 percent screened RAP materials that satisfied the Tennessee's mix criteria.(43,44) Increasing the percentage of RAP (less than 30 percent) increased the fatigue resistance; however, at a high percentage of RAP (30 percent), the mixtures became stiffer, and the addition of RAP compromised some fatigue characteristics.(43,44) Therefore, based on the results of laboratory and field mixture tests, both the Kingery and Vukosavljevic studies recommended the use of up to 20 percent RAP for Tennessee surface mixtures.(43,44) Hajj et al. in 2009 conducted bending beam fatigue tests and mechanical pavement analysis to compare the fatigue resistance of mixtures containing 0, 15, and 30 percent RAP from 3 sources and containing 2 types of virgin binder, PG 64-22 and PG 64-28.(8) For PG 64-

22 mixes, the addition of 15 percent RAP to the mix resulted in either better or equivalent resistance to fatigue cracking compared to the virgin mix, regardless of RAP source.(8) The addition of 30 percent RAP to the mix resulted in better resistance to fatigue cracking than the virgin mix only in the case of RAP from a 20-year-old HMA pavement. (8) For PG 64-28 mixes, the addition of 15 percent RAP or 30 percent RAP to the mix resulted in a significant reduction in fatigue resistance, regardless of RAP source.(8) West et al. in 2013 used IDT fracture energy tests at 50°F to evaluate the resistance to fatigue cracking of mixtures from New Hampshire, Utah, Minnesota, and Florida.(11) The fracture energy results for all four mixes showed that the virgin mixes had significantly higher fracture energy values than the high RAP content mixes, which indicates that RAP mixes had less fatigue resistance than the virgin mixtures. (11)

A few studies, however, have shown that moderate to high RAP content mixes exhibited equivalent or better fatigue resistance compared to mixtures without RAP.(9,12) For instance, Santos et al. in 2010 conducted bending beam tests and used 50 percent loss of initial stiffness modulus as the fatigue resistance criterion to study mixtures containing 0, 20, 30, and 40 percent RAP. These mixtures were produced in both a batch plant and in a laboratory.(9) Both the plant and laboratory mixtures containing RAP exhibited better fatigue resistance than the reference mixture.(9) Al-Qadi et al. in 2012 conducted controlled beam fatigue tests at 68°F at strain levels of 1000, 800, 700, 500, 400, and 300 microstrains to evaluate 8 mixtures containing 0, 30, 40, and 50 percent RAP from two areas.(12) They also used the traditional 50 percent reduction in initial stiffness failure criterion. (12) Based on the slope parameter of the fatigue curve, the fatigue resistance of HMA mixes improved slightly with the addition of RAP. (12) Also, a single-bumped down of binder grade and double-bumped down of binder grade improved the fatigue resistance of RAP mixtures over that of the control mixture.(12)

While, some studies showed that the fatigue cracking resistance of RAP mixtures depends on the test methods or RAP sources.(45,46) Shu et al. in 2008 conducted a study to investigate different test methods for assessing the fatigue characteristics of HMA mixes containing 0, 10, 20 and 30 percent RAP.(45) The fatigue test parameters included IDT strength, failure strain, a toughness index, the resilient modulus, dissipated creep strain energy threshold, energy ratio, plateau value, and load cycles to failure.(45) The study by Shu et al. found that including RAP in HMA mixtures generally increased IDT strength and reduced post-failure tenacity in IDT strength testing. (45) The dissipated creep strain energy threshold and energy ratio values decreased with an increase in RAP percentage, which indicated that the addition of RAP negatively affected the fatigue resistance of the mix. (45) However, the plateau values obtained from the beam fatigue tests contradicted those findings and showed that higher RAP contents led to more resistance to fatigue. (45) The number of cycles needed to attain a 50 percent decrease in stiffness was also higher for the higher RAP percentage mixes than for the virgin mix.(45) Sabahfar et al. in 2014 conducted semi-circular bending and overlay tester tests at 77°F to study the cracking resistance of mixtures containing 20, 30, and 40 percent RAP from two areas (Shilling and Konza) in Kansas.(46) Their cracking test results did not follow the same pattern for the two sources of RAP. (46) For the mixtures containing RAP from the Shilling area, the cracking resistance decreased as the percentage of RAP in the mixture increased, whereas for the mixtures containing RAP from the Konza area, the mixture with the highest RAP content (40 percent) exhibited the most cracking resistance.(46)

Overall, studies have reported mixed findings regarding the effects of RAP on fatigue cracking. The discrepancies could be attributed to the test method, RAP source, etc. Moreover, the addition of RAP affects the modulus of the mixes and thus, in a pavement structure, the pavement responses would differ for layers with different RAP percentages. The use of the same stress or strain level for fatigue tests for different mixes is a questionable prospect. Therefore, the proper selection of a laboratory performance test that is related to field performance is imperative for the performance evaluation of HMA mixtures containing high RAP percentages.

Low Temperature Thermal Cracking Resistance

The semi-circular bending test, bending beam rheometer (BBR) creep test, and thermal stress-restrained specimen test (TSRST) can be used to evaluate the low temperature thermal cracking resistance of asphalt mixtures. Generally, studies have found that mixes containing RAP are more susceptible to low temperature cracking than mixes without RAP; however, the use of soft virgin binder with a high RAP content can reduce the stiffness of mixes and improve their thermal cracking resistance.(5,12,47)

Li et al. in 2008 used the semi-circular bending test to evaluate ten asphalt mixtures from two different RAP sources that included 3 RAP percentages (0, 20, and 40 percent) and 2 asphalt binders (PG 58-28 and PG 58-34), which met the Minnesota Department of Transportation's Superpave mix design criteria.(5) Li et al. used the fracture energy parameter to evaluate the effects of RAP content on the mixtures. The semi-circular bending test results showed that the fracture energy decreased as RAP content increased. (5) The control mixtures showed the highest fracture energy values. (5) The 20 percent RAP mixtures had similar fracture resistance to the control mixtures. However, the mixes with 40 percent RAP exhibited significantly lower low-temperature fracture resistance than control mix.(5)

Loria et al. in 2011 performed a study to evaluate the impact of high RAP content on thermal cracking using TSRST after multiple freeze-thaw cycles.(47) The mixes, produced according to the Marshall mix design method, used 3 RAP contents: 0, 15, and 50 percent. The study employed PG 58-28 binder for all the mixes. The study also tested an additional 50 percent RAP mix with PG 52-34 virgin binder. The test method is to cool a 2-inch by 2-inch by 10-inch beam specimen at a rate of 18°F/hour while restraining it from contracting. (47) The temperature at which fracture occurs is referred to as the "fracture temperature" which provides a qualitative assessment of the mixes' resistance to low temperature thermal cracking. TSRST fracture temperatures for 0 percent RAP and 15 percent RAP specimens were very similar to the virgin binder low critical temperature. (47) The 50 percent RAP content specimens had TSRST temperatures that were several degrees warmer than the virgin binder, indicating decreased thermal cracking resistance. (47) Using a soft virgin binder improved TSRST fracture temperature for 50 percent RAP mixes.(47)

Al-Qadi et al. in 2012 also used semi-circular bending tests to evaluate eight mixtures containing 0, 30, 40, and 50 percent RAP from 2 areas (Districts 1 and 5 of Illinois DOT) and the effect of binder grade bumping on the improvement of low temperature performance.(12) For both of 2 districts' mixes, the mixtures with an addition of 30 percent RAP increased the potential for thermal cracking as the fracture energy decreased. (12) Further additions of RAP (40 and 50 percent) did not lead to significantly different fracture behavior from HMA with 30 percent RAP, and the fracture energy values still remained lower than those of the control mix. (12) When RAP mixes used a single-bumped binder grade, the low temperature fracture resistance improved marginally. (12) When RAP mixes used a double-bumped binder, the low temperature fracture behavior improved over the no-bumping behavior and showed a slight improvement over HMA mix that used a single-bumped binder grade. (12) Hence, the Al-Qadi et al. study recommended double bumping the binder grade for mixtures with 30 percent or more RAP to reduce the thermal cracking potential.(12)

However, a few studies showed contradicting results.(8,11) Hajj et al. in 2009 measured the thermal cracking resistance of mixes containing 0, 15, and 30 percent RAP from 3 sources and 2 types of virgin binder, PG 64-22 and PG 64-28.(8) Their TSRST results showed that for PG 64-22 mixes, the addition of 15 percent RAP or 30 percent RAP to the mix resulted in either better or equivalent resistance to thermal cracking, regardless of the source of RAP. (8) For PG 64-28 mixes, the addition of 15 percent RAP or 30 percent RAP resulted in significantly better resistance to thermal cracking than the control mix, regardless of the source of RAP.(8) West et al. in 2013 used 2 test methods, the semi-circular bending fracture test and BBR creep test to evaluate the low temperature performance of RAP mixtures from New Hampshire, Utah, and Minnesota.(11) The fracture toughness and fracture energy values computed from the semi-circular bending test, and the creep stiffness values and m-values obtained from BBR test were able to characterize the mixtures' ability to resist thermal cracking. Ideally, the mixes with higher fracture toughness and fracture energy values would be expected to perform better than mixes with low fracture properties. (11) The two fracture properties obtained from the semi-circular bending test were conflicting. Compared to the corresponding virgin mixes, the high RAP mixes generally had higher fracture toughness values, but similar or lower fracture energy values. (11) For BBR test results, the mixes containing RAP generally had higher stiffness values and lower m-values than the virgin mixes, which theoretically should result in more cracking. (11) However, analysis of the critical cracking temperatures for the climates where the materials originated indicated that the high RAP content mixes would perform similarly to the corresponding virgin mixes with regard to thermal cracking.(11)

In summary, most of the studies indicate that increasing RAP percentage could compromise thermal cracking resistance. The use of soft binder could help mitigate thermal cracking. However, the mixed test results regarding thermal cracking suggest that further studies are warranted, especially for local materials. RAP mixes may enhance the pavement structure by reducing the critical tensile strains in the pavement.

Laboratory Performance of Plant-Produced RAP Mixes

In addition to the laboratory mechanical analysis of RAP mixture performance, the effects of plant production parameters on the degree of blending and RAP mixture performance also have raised concerns.

A study by Mogawer et al. in 2012 included 18 plant-produced HMA mixes that contained RAP up to 40 percent with a nominal maximum aggregate size (NMAS) of both 9.5-mm and 12.5-mm.(13) The authors studied the characteristics of these mixes, which came from three projects located in the

Northeastern United States. They performed different binder and mixture tests to determine the effects of RAP on field performance. Their investigation found that it is essential to document how RAP mixes are handled and produced, as differences in the recorded production parameters affected the degree of blending between RAP and virgin binders. (13) Mogawer et al. also found that the production parameters affected the workability and performance of mixtures. (13) Their results showed that the use of a softer virgin binder may improve the low temperature properties of RAP mixes. (13) Also, results of their overlay tester tests showed that cracking resistance decreased with an increase in RAP content; these results agree with the results from the low temperature tests on recovered asphalt binder.(13)

McDaniel et al. in 2012 conducted research on the performance characteristics of plant-produced HMA mixtures.(37) The objective of this study was to use the high and low temperature properties of plant-produced RAP mixtures to evaluate whether the current tiered guidelines for RAP usage were valid. The study investigated several factors that could possibly affect the thoroughness of the blending between virgin and RAP binder, such as plant type, mixing temperature, the amount of mixing, etc. Their results showed that the stiffness of the mixtures increased with an increase in RAP, especially at intermediate and high temperatures. (37) However, statistically, this increase was not significant all the time. (37) The authors suggested that both the grade of the virgin binder and the amount of RAP affected the increase in the dynamic modulus value. (37) The stiffening effect of RAP binder was more significant for mix with softer virgin binder grade than for mix with stiffer virgin binder grade.(37)

Apeagyei et al. in 2011 conducted a study in Virginia to evaluate the rutting resistance of 19 plant-produced asphalt mixtures with up to 25 percent RAP.(48) Their dynamic modulus test results showed that the stiffness values of the control (virgin) mixes were similar to those of 25 percent RAP mixtures. (48) Apeagyei et al. also conducted flow number tests at 129.2°F that showed that at moderate RAP contents (10 and 15 percent), the mixtures exhibited better rutting resistance than mixtures with a high RAP content and the control mixtures. (48) Statistical analysis indicated that RAP content was the major factor that affected rutting resistance in the studied mixtures. (48) The authors suggested that the reason for the decrease in the flow number values at high RAP contents may be linked to the practice of using soft binder at this level and incomplete blending.(48)

Field Performance of RAP Mixes

The Louisiana Transportation Research Center (LTRC) conducted a comparative study of five RAP projects and five conventional construction projects.(49) The field evaluation portion of the study included performance in terms of type of distress, serviceability, and structure over a life span. The results showed that the performance of the pavements with 20 percent RAP to 50 percent RAP was similar to that of conventional pavements, and no significant differences were evident in terms of serviceability rating and pavement condition.(49)

The State of Georgia in 1995 also conducted a research project to compare the performance of pavements with RAP with virgin (control) asphalt pavements.(50) The Georgia Department of Transportation constructed five projects; each one consisted of a recycled section and control section. The recycled sections contained RAP percentages between 10 and 25 percent. The performance evaluation showed no significant differences between the test sections of the pavements with and without RAP in terms of rutting, fatigue cracking, and raveling for a service period from 18 to 27 months. (50) The study's conclusion was that RAP mixtures perform similarly to virgin mixtures. (50 Laboratory experiments of field cores in the study also showed comparable results for RAP and virgin sections.(50) It shall be noted that the service period is relatively short, up to 27 months, which may not be sufficiently long to differentiate the difference in performance.

In 2008, the Virginia Department of Transportation (VDOT) investigated the effects of increased RAP percentages on pavement performance and mixture costs for projects from 3 VDOT districts that used more than 20 percent RAP.(51) VDOT also sampled and tested mixes containing less than 20 percent RAP for comparative purposes. The results of laboratory tests showed no significant differences between the performance of high RAP mixes and control mixes in terms of rutting, fatigue, and moisture susceptibility. (51) Furthermore, the study showed no construction problems associated with the use of high RAP mixes. (51) Some slight price adjustments were necessary, but they were not due to the use of high RAP mixes. (51) Also, the addition of RAP raised the high temperature grading one to two grades, which should be a consideration for mix design.(51)

Carvalho et al. in 2010 investigated short- and long-term RAP mix performance in overlays and compared the results to the performance of virgin hot asphalt mixes.(52) The study included records of 18 projects from the Long-Term Pavement Performance (LTPP) program in the United States and Canada. The collected performance data represented periods ranging from 8 to 17 years. The evaluation of the pavement responses included three main distress parameters: rutting, roughness, and fatigue cracking. The results obtained from analysis of variance (ANOVA) showed that the performance of RAP overlays was statistically similar to that of virgin HMA overlays, and that RAP overlays can provide structural improvements that are equivalent to virgin HMA overlays in terms of deflection.(52)

West et al. in 2013 conducted research to develop guidelines for mixtures with high RAP contents, i.e., from 25 to 55 percent.(11) They found that asphalt pavements containing up to 50 percent RAP showed positive performance in diverse climates and under various traffic conditions. (11) West et al. reported that many researchers have studied the data obtained from experimental sections in LTPP program pavements to compare RAP and virgin mixes for overlays. (11) Those studies indicate that the performance of mixes containing 30 percent RAP is the same as or better than that of virgin mixes. (11) RAP mixes exhibited more wheel-path cracking than the virgin mixes. (11) Recent results from the National Center of Asphalt Technology (NCAT) test track show that using soft virgin binder improves the cracking and raveling resistance of surface mixes.(11)

Summary

RAP characterization studies have investigated the use of both the ignition oven method and chemical extraction method to determine the binder content and gradation of RAP aggregate. Cares must be taken when ignition oven is used to extract RAP aggregate if the type of RAP aggregate is likely to break down or be lost under the extreme temperature in the ignition oven. The determination of the bulk specific gravity of RAP aggregate must be precise, because even a small error in the bulk specific gravity value will amplify the error in calculating VMA. The three current methods for determining bulk specific gravity have their merits and drawbacks. Also, the performance grade of recovered RAP binder needs to be determined if a mixture contains high percentages of RAP.

Appropriate processing, such as fractionation, could help reduce RAP variability in terms of binder content and gradation; then, RAP variability would not be a limitation to increase RAP content in asphalt mixes. However, currently, proper virgin binder selection is still a challenge when trying to achieve comparable performance between mixes with high RAP content and mixes without RAP due to the complex issue of blending between RAP binder and virgin binder. The effect of high percentages of RAP on moisture susceptibility is limited, and the addition of anti-stripping additives can help improve moisture damage resistance for mixes with RAP.

Most of the studies cited in this literature review indicate that the use of RAP in asphalt mixtures could produce mixtures that perform better than virgin mixes in terms of resistance to permanent deformation because of the aged binder in RAP. However, RAP mixes also could reduce fatigue resistance or cause brittle behavior if the mix design employs high percentages of RAP. On the other hand, at low percentages of RAP (less than 20 percent), the fatigue cracking resistance seems to be improved with the addition of RAP. A few studies have shown that moderate and high RAP content mixes exhibited equivalent or better fatigue resistance compared to mixtures without RAP. Mixes containing RAP were more susceptible to low temperature cracking. However, the use of soft virgin binder in high RAP mixes was able to reduce the stiffness of the mixes and improve the thermal cracking resistance. A few studies showed contradicting results, highlighting the importance of selecting the proper test method.

Many studies also indicated that the field performance of RAP mixtures was not significantly different from that of virgin mixtures in terms of rutting, fatigue, and moisture susceptibility, but at high RAP percentages, the mixture performance results were mixed.

Chapter 3
RAP Characterization and Mix Design

This chapter presents the test methods and results of RAP characterization in terms of binder content, RAP aggregate gradation, bulk specific gravity (G_{sb}) of RAP aggregate, and PG of the extracted RAP binder. This chapter also presents ten mix designs with different percentages of RAP and their volumetric properties.

Materials and Methods

RAP Characterization

This research project used two different sources for RAP materials. One RAP material, referred to as North RAP, was from a rehabilitation project on US-95 from Garwood to Sagle at Northern Idaho. The other RAP material, referred to as South RAP, was from a section of US-95 from Wilder to Parma in Southern Idaho. In order to control the variability of RAP materials, the research team dried them by heating them to 230°F until the sample weight difference measured every hour was less than 0.1 percent. The researchers then fractionated RAP materials into coarse RAP and fine RAP based on No.4 screen, homogenized each portion in a concrete mixer, and recombined them for RAP characterization and mix design according to the original weight ratio of the coarse RAP and fine RAP materials after homogenization. The weight ratio was 0.53:0.47 for North RAP and 0.41:0.59 for South RAP. The characterization of both North RAP and South RAP materials included binder content, RAP aggregate gradation, the bulk specific gravity of RAP aggregate, and PGs of the extracted and recovered RAP binders.

The research team used the chemical extraction method according to *AASHTO T164-14*, *Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)*, and the ignition oven method according to *AASHTO T308-10*, *Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix Asphalt (HMA) by the Ignition Method*, without a correction factor, to determine the binder content of RAP materials.(16,17) Following the chemical extraction procedure, the researchers recovered the extracted RAP binder according to *AASHTO R59-11*, *Standard Practice for Recovery of Asphalt Binder from Solution by Abson Method*, using nitrogen for cooling and toluene/ethanol as solvent.(53) In order to be consistent with the field mix design, the researchers considered the binder content results from the chemical extraction method to be true values and then used these values in the mix design to calculate the percentage of binder replacement for the mixes. The researchers used *AASHTO T30-14, Standard Method of Test for Mechanical Analysis of Extracted Aggregate*, to determine the gradations of the extracted RAP aggregate obtained from both the chemical extraction method and ignition oven method and then to compare the gradations determined from these two extraction methods.(54) Then, the researchers used RAP gradation results from the chemical extraction method in the mix design calculations.

Chapter 2 provides discussion of the methods used to determine the bulk specific gravity of RAP aggregate. For this project, the researchers extracted the aggregate using the ignition oven method to determine the bulk specific gravity of coarse RAP aggregate and fine RAP aggregate separately in accordance with *AASHTO T85-14*, *Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate*, and *Idaho IT-144-08, Specific Gravity and Absorption of Fine Aggregate Using Automatic Vacuum Sealing (CoreLok) Method*, respectively.(21,55) In order to verify the effects of the ignition oven method on the changes in the bulk specific gravity of the aggregate and to determine the accuracy of this approach, the team mixed the virgin aggregate (with known bulk specific gravity) with different amounts of binder and then compacted the mix in the gyratory compactor. After that, the researchers heated the compacted samples in the oven at 230°F to break up the samples into loose mixes for extraction using the ignition oven. Then, the team determined the bulk specific gravity of the extracted aggregate and compared the results with the bulk specific gravity values before extraction, as shown in Table 1. The difference between the bulk specific gravity values before and after extraction was smaller than the difference two-sigma limit (d2s). Therefore, the two specific gravity values were considered to be identical. In short, this project utilized the ignition oven method to extract RAP aggregate and to determine the bulk specific gravity values of coarse RAP aggregate and fine RAP aggregate.

Table 1. Comparison of Aggregate Bulk Specific Gravity Before and After Ignition Oven Extraction

	Bulk Specific Gravity					
	Before Extraction	**Binder Content (%)**				**d2s**
		4.3	**4.8**	**5.3**	**5.8**	
		After Extraction				
Coarse Aggregate	2.669	2.653	2.649	2.645	2.647	0.025
Fine Aggregate	2.667	2.681	2.675	2.676	2.679	0.034[A]
Combined	2.668	2.665	2.660	2.659	2.661	-

[A] The bulk specific gravity test used for fine aggregate is IT-144-08, whereas d2s is from AASHTO T84-13.

According to the method proposed by McDaniel et al. in 2001 to determine the recovered RAP binder PG , the research team used a dynamic shear rheometer (DSR) to test the recovered RAP binder at a high temperature as if the binder was the original binder. Then, the research team aged RAP binder in RTFO and tested it in DSR and BBR to determine the critical temperature and PG of RAP binder without using a pressure aging vessel.(4) The researchers obtained all of these test results from three samples and then calculated the average values and coefficients of variation (COVs).

Mix Design

This research used 2 field project mix designs as reference mixes; these 2 reference mixes incorporated 2 RAP sources, respectively. One field project was a section of US-95 from Garwood to Sagle at Northern Idaho. The North laboratory mixes with 0, 17, 30, and 50 percent RAP binder replacement were used in laboratory mix designs based on the Garwood project and are referred to in this study as N0, N17, N30, and N50. The field loose mix with 30 percent RAP binder replacement from the Garwood field project is referred to as NF30. The other project was a section of US-95 from Wilder to Parma at Southern Idaho. The South laboratory mixes with 0, 17, 26, and 50 percent RAP binder replacement were used in the laboratory mix designs based on the Wilder project and are referred to in this study as S0, S17, S26, and S50. The field loose WMA mix with 26 percent RAP binder replacement from the Wilder project is referred to as SF26. Therefore, this study investigates a total of 10 mixes, including 8 laboratory HMA mixes, 1 field plant HMA mix (NF30), and 1 field plant WMA mix (SF26). However, WMA field loose mix was reheated in the laboratory for sample preparation and should be considered as a HMA mix.

North Mix Designs

The targeted mix designs for the North mixes included a 19-mm NMAS with a mixture class designation of SP5 and traffic level of 10 to 30 million equivalent single axle loads (ESALs). The mineralogy of both virgin aggregate and RAP aggregate used in all of North mixes was granite. The volumetric requirements included air void content of 4.0 percent, minimum VMA of 13.0 percent, VFA of 65 to 75 percent, and dust-to-asphalt ratio of 0.8 to 1.6. In order to control the final blended gradation of the aggregate (including RAP) shown in Table 2, the research team adjusted the gradation of virgin aggregate to make the final gradations of all the mixes the same as that of the mix design of the field project. The targeted PG of the asphalt was PG 58-28. Based on ITD specifications, PG of the virgin binder used in N0 and N17 was PG 58-28, and PG of the virgin binder used in N30 and NF30 was PG 52-34.(1) Based on the blending chart, a PG of 40-34 was supposed to be used for N50. However, PG 40-34 binder was not readily available in the local market and would have been cost-prohibitive for a contractor to use. Therefore, after consulting with ITD, the team decided to use PG 52-34 binder instead. This choice provided an opportunity to examine the effectiveness of the use of the higher PG that was available in the market to replace the unrealistically low PG binder as per the blending chart. Table 3 presents PGs of virgin binders and PGs of blended binders for the North mixes. The researchers calculated the grades of the blended binders based on the assumption that RAP binder and virgin binder were blended together completely.

Table 2. Final Blended Gradations of North and South Mixes

	Sieve Size (mm)										
	25.0	**19.0**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
North Mix (% Passing)	100	98	82	69	45	29	19	13	9	7	5.9
South Mix (% Passing)	100	100	95	84	62	47	35	26	16	9	5.5

Table 3. Performance Grades of Final Blended Binders of North Mixes

North Mixes	PG of Virgin Binder	PG of RAP Binder	PG of Blended Binder	Target PG of Binder
N0	58-28 (Target)	-----	58-28	58-28
N17	58-28	75.8-23.6	61.0-27.3	
N30	52-34		59.1-30.9	
N50	52-34 (40-34[A])		63.9-28.8	
NF30	52-34		59.1-30.9	

[A] Based on blending chart, but not available in local market.

The research team obtained the optimum binder content of each North mix by determining the volumetric properties of the mixtures at 4 trial binder contents of 4.3, 4.8, 5.3 and 5.8 percent. Prior to mixing the virgin aggregate with the virgin binder, the researchers heated the virgin aggregate at the mixing temperature of 280°F for 3 hours, mixed the dried RAP with the virgin aggregate, and then heated the mixed RAP and virgin aggregate at the mixing temperature for another 2 hours prior to mixing with the virgin binder. The compaction temperature of the North laboratory mixes was 260°F. The research team used the methods specified in *AASHTO T209-12*, *Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Hot Mix Asphalt (HMA)*, and *AASHTO T166-13, Standard Method of Test for Bulk Specific Gravity (G_{mb}) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens*, to determine the maximum specific gravity (G_{mm}) of loose mixes and the bulk specific gravity (G_{mb}) of compacted samples, respectively.(56,57) After consulting with ITD, the researchers conducted the moisture susceptibility test only for the mix with the highest RAP percentage, i.e., N50, in the laboratory according to *AASHTO T165-02*, *Effect of Water on Compressive Strength of Compacted Bituminous Mixtures*.(58) If the researchers had found that the moisture susceptibility of N50 was a concern, they would have conducted more tests on other mixes. The anti-stripping agent used was MORLIFE 5000 at 0.5 percent of the optimum binder content of N50 and NF30.

South Mix Designs

The targeted mix designs for the South mixes included a 12.5-mm NMAS with a mixture class designation of SP4 and a traffic level of 3 to 10 million ESALs. The mineralogy of both virgin aggregate and RAP aggregate used in all of South mixes was Quaternary alluvium. The volumetric requirements included air void content of 4.0 percent, minimum VMA of 14 percent, VFA of 65 to 75 percent, and dust-to-asphalt ratio of 0.6 to 1.2. Again, the research team controlled the final blended gradations of all the South laboratory mixes the same as for the South field mixes, as shown in Table 2. The targeted final blended asphalt was PG 70-28. Based on ITD specifications, PG of the virgin binder used in S0 and S17 was PG 70-28 and PG of the virgin binder used in S26 and SF26 was PG 64-34.(1) Based on the blending chart, PG of the virgin binder used in S50 was supposed to be PG 58-40. However, based on market availability and after consulting with ITD, the researchers used PG 58-34 for S50. Table 4 presents PGs of virgin binders and PGs of blended binders for the South mixes.

Table 4. Performance Grades of Final Blended Binders of South Mixes

South Mixes	PG of Virgin Binder	PG of RAP Binder	PG of Blended Binder	Target PG of Binder
S0	70-28 (Target)	-----	70-28	70-28
S17	70-28	85.2-16.8	72.6-26.1	
S26	64-34		69.5-29.5	
S50	58-34 (58-40[A])		71.6-25.4	
SF26	64-34		69.5-29.5	

[A] Based on blending chart.

The research team determined the optimum binder content for each South mix using a similar procedure as for the North mixes with 4 different binder contents of 4.5, 5.0, 5.5 and 6.0 percent. The mixing and compaction temperatures for the South mixes were 320°F and 299°F, respectively. The heating procedure prior to mixing was the same as for the North mixes. Again, after consulting with ITD, the researchers conducted the moisture susceptibility test only for the mix with the highest RAP percentage, i.e., S50, in the laboratory with 0.5 percent anti-stripping agent. If the researchers had found that the moisture susceptibility for S50 was a concern, they would have conducted more tests on other mixes. The anti-stripping agent used was MORLIFE 5000 at 0.5 percent of the optimum binder content of S50 and SF26.

Results and Discussion

Characterization of North RAP and North Mix Designs

Figures 5 and 6 present the results for the binder contents and RAP aggregate gradations of the North RAP, respectively. The ignition oven method determined the binder content to be 4.9 percent, which is slightly higher than the binder content of 4.5 percent determined from the chemical extraction method. The possible reason for this difference is that the test temperature of 1,000°F during the ignition oven process may have burned away some of the mineral aggregate. As for RAP aggregate gradations, the results from the two extraction methods were close to each other. In order to be consistent with the field mix design, the research team used the results for the binder content and gradation from the chemical extraction method for the mix design of mixes with different RAP contents.

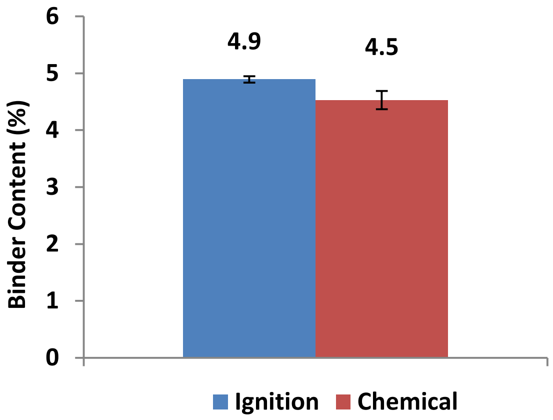


Figure 5. Binder Content of North RAP

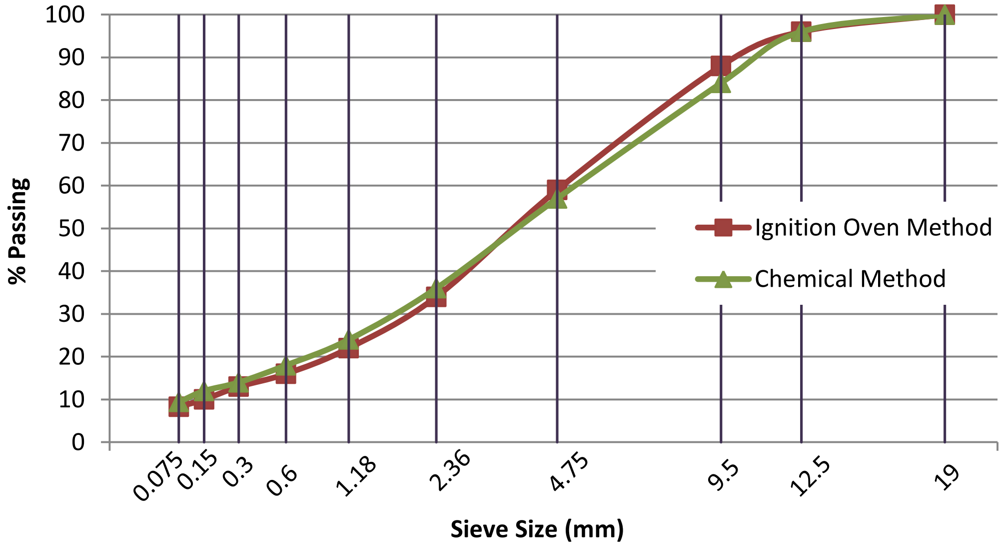


Figure 6. Gradation of North RAP Aggregate

Tables 5 and 6 present the results of the bulk specific gravity values of the North RAP aggregate extracted using the ignition oven method and PG of the recovered North RAP binder, respectively. The combined bulk specific gravity value of the North RAP aggregate is 2.618, calculated according to the ratio of the coarse RAP aggregate to the fine RAP aggregate (0.43:0.57) and based on the gradation of the North RAP aggregate. PG of the recovered North RAP binder is PG 70-22.

Table 5. Bulk Specific Gravity of North RAP Aggregate

	Sample #1	Sample #2	Sample #3	Average	Standard Deviation	COV (%)
Coarse RAP Aggregate	2.604	2.604	2.611	2.606	0.004	0.15
Fine RAP Aggregate	2.618	2.628	2.635	2.627	0.009	0.33
Combined (0.43:0.57)	2.618					

Table 6. Performance Grade of Recovered North RAP Binder

	PG of Recovered North RAP Binder						
	Sample #1	**Sample #2**	**Sample #3**	**Average**	**Standard Deviation**	**COV (%)**	**PG**
High Temperature	76.9	74.9	75.5	75.8	1.026	1.35	70
Low Temperature	-22.7	-24.6	-23.6	-23.6	0.950	4.02	-22

Figure 7 presents the results of the optimum asphalt contents and volumetric properties of the North mixes with different percentages of RAP. Appendix A provides details regarding the mix design results. The red lines in Figure 7 signify the allowable limits based on ITD specifications. Figure 7 shows that the total optimum binder contents of all the mixes are close to each other, with a maximum difference of 0.4 percent. The volumetric properties of all the North mixes, including air void content, VMA, VFA, and dust-to-asphalt ratio, satisfy ITD specification requirements.

Table 7 presents the moisture susceptibility test results for N50 and NF30, which are based on the retained unconfined compressive strength values as the ratio of wet strength to dry strength. The ratios for N50 and NF30 are 113 percent and 92 percent, respectively, which both pass the minimum specification requirement of 85 percent. Therefore, the mixes with high percentages of RAP were not susceptible to moisture damage with the addition of an anti-stripping agent into the mixes.

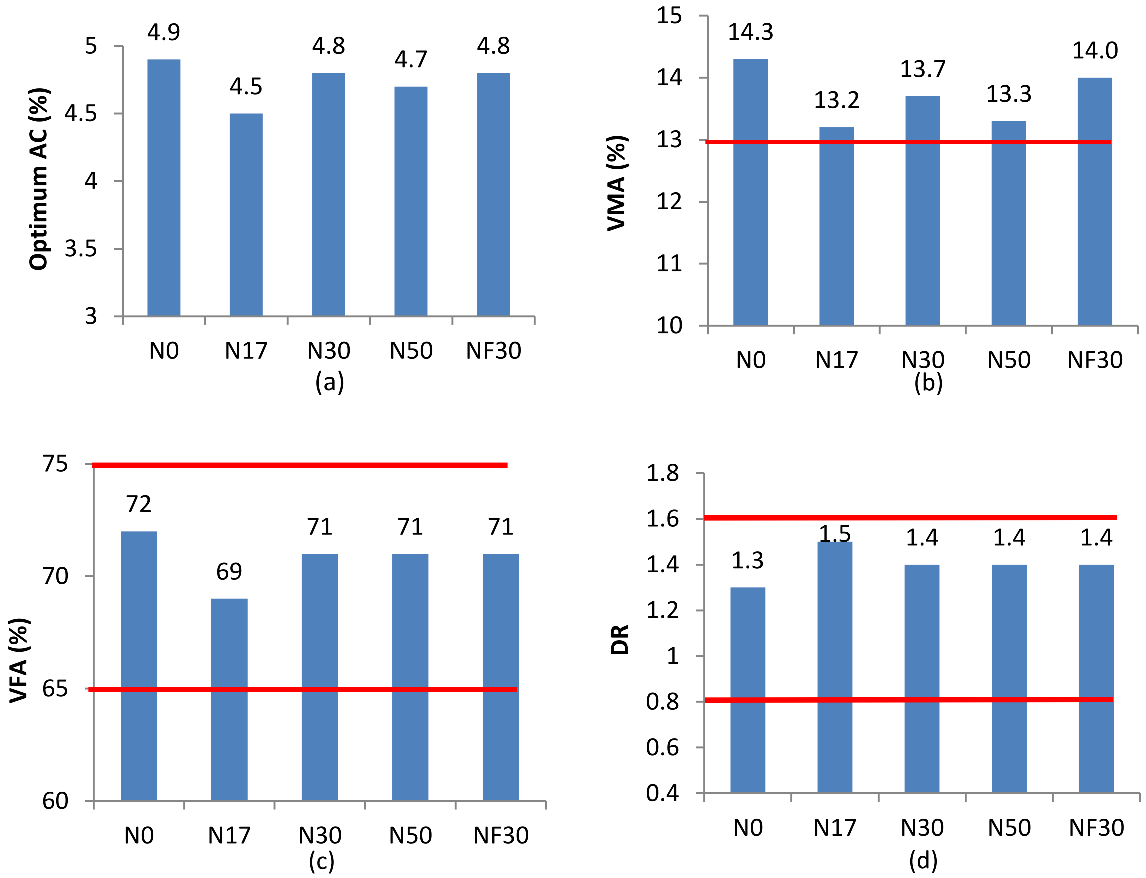


Figure 7. Mix Design Results of North Mixes: (a) Optimum Binder Content, (b) VMA, (c) VFA, and (d) Dust-to-Asphalt Ratio (DR)

Table 7. Moisture Susceptibility of North Mixes

Mixes	%Anti-stripping	Air Void (%)	Dry Strength (psi)	Wet Strength (psi)	% Retained Strength	Spec.
N50	0.5	5.7	352	399	113	85% min.
NF30	0.5	6.5	535	494	92	

Characterization of South RAP and South Mix Designs

Figures 8 and 9 present the binder contents and RAP aggregate gradations of the South RAP, respectively. The binder content determined from the ignition oven method is 5.6 percent, which is higher than the binder content of 4.9 percent obtained from the chemical extraction method. The difference between the ignition oven method and chemical extraction method for the South RAP is 0.7 percent, which is higher than the difference of 0.4 percent for the North RAP. It seems that the South RAP aggregate was more susceptible to being burned away during the ignition process than the North RAP aggregate. As for the gradation of the South RAP aggregate, the results from the two extraction methods were close to each other, which is similar to the gradation results for the North RAP aggregate. Therefore, based on the results for the binder contents and aggregate gradations for both the North RAP and South RAP materials, the chemical extraction method appears to be more reliable for determining binder content and RAP aggregate gradation than the ignition oven method. If the ignition oven method must be used, then a correction factor for the binder content would be needed.

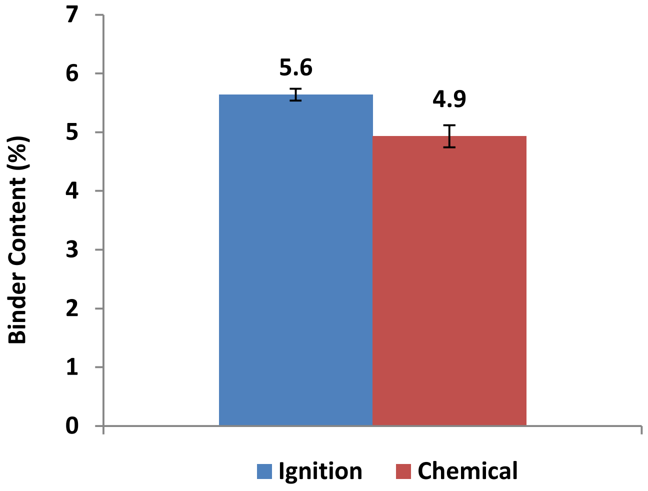


Figure 8. Binder Content of South RAP

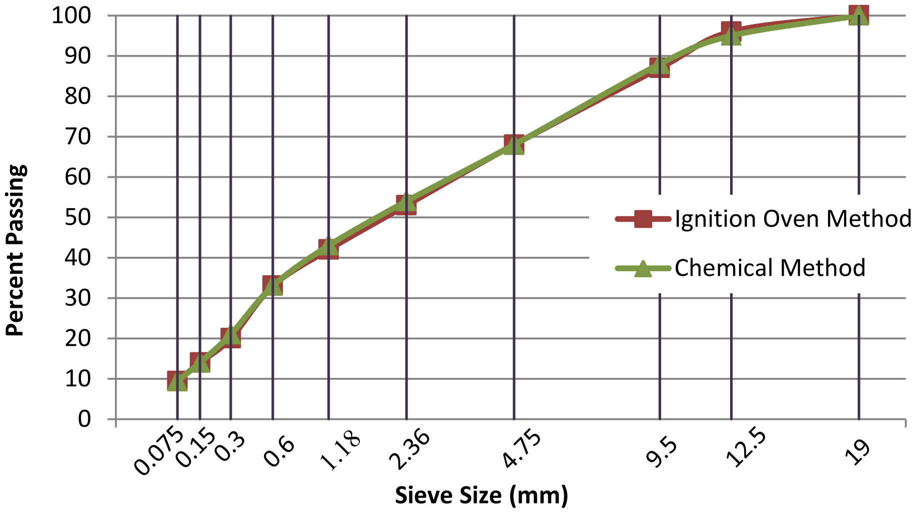


Figure 9. Gradation of South RAP Aggregate

Tables 8 and 9 present the results for the bulk specific gravity of the South RAP aggregate extracted using the ignition oven method and PG of the recovered South RAP binder, respectively. The combined bulk specific gravity value of the South RAP aggregate is 2.583, as calculated according to the ratio of coarse RAP aggregate to fine RAP aggregate (0.32:0.68) and based on the gradation of the South RAP aggregate. PG of the recovered South RAP binder is PG 82-16, which is significantly higher than PG (PG

70-22) of the North RAP binder. The high PG of South RAP binder may be because stiff virgin binder was often used in South Idaho based on LTPPBind software, when compared to North Idaho.

Table 8. Bulk Specific Gravity of South RAP Aggregate

	Sample #1	Sample #2	Sample #3	Average	Standard Deviation	COV (%)
Coarse RAP Aggregate	2.580	2.554	2.543	2.559	0.019	0.75
Fine RAP Aggregate	2.596	2.586	2.601	2.594	0.008	0.29
Combined (0.32:0.68)	2.583					

Table 9. Performance Grade of Recovered South RAP Binder

	PG of Recovered South RAP Binder						
	Sample #1	**Sample #2**	**Sample #3**	**Average**	**Standard Deviation**	**COV (%)**	**PG**
High Temperature	85.3	85.1	85.1	85.2	0.115	0.14	82
Low Temperature	-17.0	-16.7	-16.8	-16.8	0.153	0.91	-16

Figure 10 presents the results of the optimum asphalt contents and volumetric properties of the South mixes with different percentages of RAP. Table 14 of Appendix A presents details regarding the mix designs. The total optimum binder contents of all the mixes are close to each other, with a maximum difference variation of 0.4 percent. Again, by controlling the final blended gradation, the volumetric properties of the South mixes, including air void content, VMA, and VFA, satisfy ITD specification requirements. The only exception is the dust-to-asphalt ratio for S50 mix, which slightly exceeded the specification of 1.2, because the South field mix has a dust-to-asphalt ratio of 1.2, which is on the specification limit. Still, the inclusion of high percentage RAP did not affect the dust-to-asphalt ratio and other volumetric properties significantly.

Table 10 presents the moisture susceptibility test results for S50 and SF26. The ratios of wet strength to dry strength for S50 and SF26 are 97 percent and 98 percent, respectively, which pass the minimum specification requirement of 85 percent. Again, the mixes with high percentages of RAP were not susceptible to moisture damage with the addition of an anti-stripping agent into the mixes.

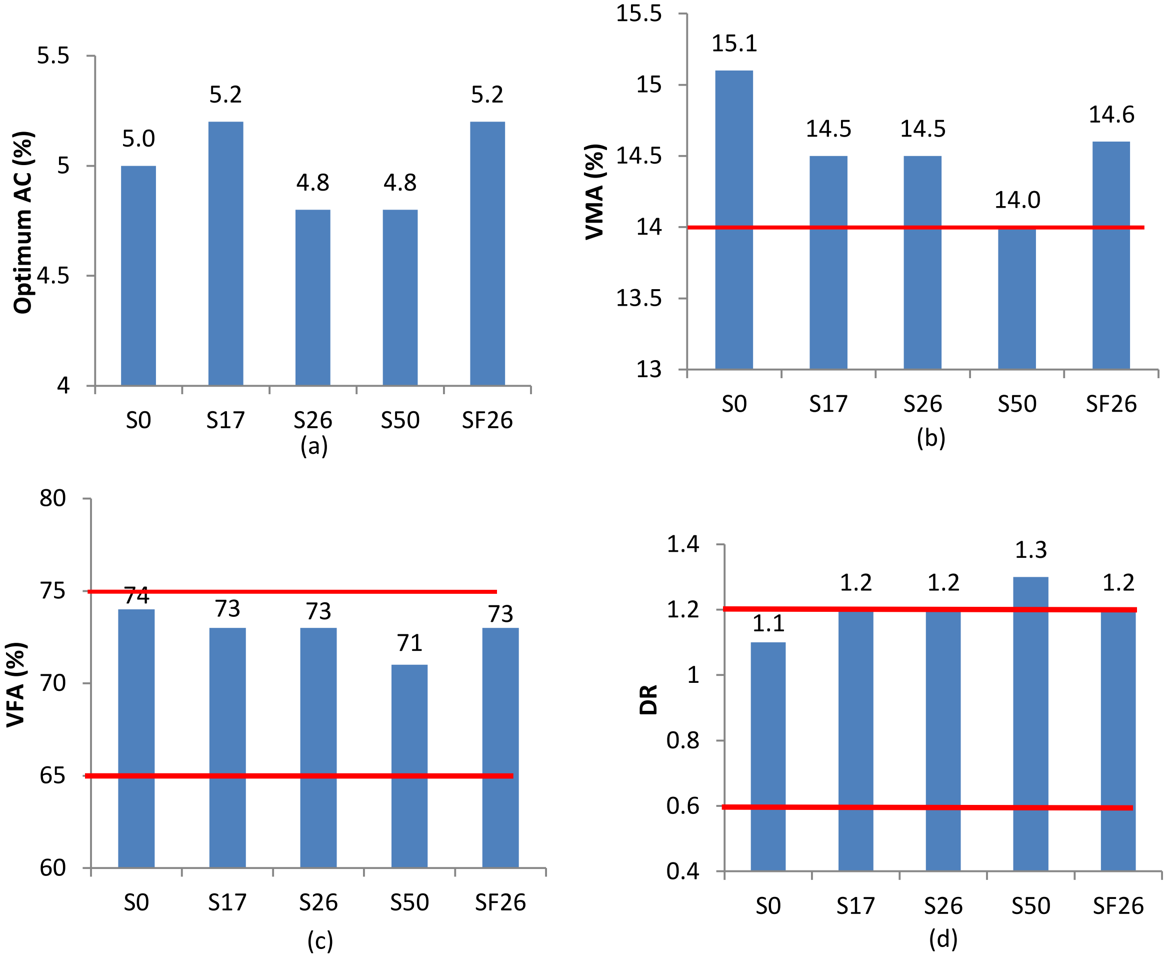


Figure 10. Mix Design Results of South Mixes: (a) Optimum Binder Content, (b) VMA, (c) VFA, and (d) Dust-to-Asphalt Ratio (DR)

Table 10. Moisture Susceptibility of South Mixes

Mixes	% Anti-stripping	Air Void (%)	Dry Strength (psi)	Wet Strength (psi)	% Retained Strength	Spec.
S50	0.5	6.6	684	664	97	85 min
SF26	0.5	6.4	484	474	98	

Summary

The research team characterized the North RAP and South RAP materials obtained from two sources in terms of binder content, RAP aggregate gradation, bulk specific gravity of RAP aggregate, and PGs of the recovered RAP binders. RAP binder contents that the team determined using the ignition oven method were higher than those determined from the chemical extraction method. RAP aggregate gradations were close to each other, regardless of the extraction method used. Because RAP aggregate might be vulnerable to being burned away during the ignition oven process, the chemical extraction method appears to be more reliable for determining the binder content and RAP aggregate gradation than the ignition oven method. The research team also determined PG of the recovered RAP binders using for the blending chart study during the mix designs.

In terms of mix design, the research team was able to control the final blended gradations of the mixes to maintain consistency with the field plant mixes. The team selected PGs of virgin binders of the mixes with different percentages of RAP based on ITD specifications and the availability of the binder in the local market. For both the North mixes and South mixes, the total optimum binder contents of the mixes with different percentages of RAP were close to each other, with a maximum difference variation of 0.4 percent. Furthermore, the volumetric properties of both the North mixes and South mixes, including air void content, VMA, and VFA, satisfied ITD specification requirements. Also, the mixes with high percentages of RAP were not susceptible to moisture damage with the addition of an anti-stripping agent into the mixes. Therefore, the mix designs of mixes containing up to 50 percent RAP were able to meet ITD specification requirements.

Chapter 4

Laboratory Performance Evaluation of HMA with RAP

This chapter presents the methods and results of laboratory performance testing for North and South mixes containing different percentages of RAP in terms of rutting resistance, fatigue cracking resistance, and low temperature thermal cracking resistance.

Rutting Resistance

The research team used flow number and gyratory stability tests to determine the rutting resistance of the mixes. The team also measured dynamic modulus values to evaluate the effects of RAP on the stiffness of the mixes and utilized the flow numbers to describe the rutting resistance that was due to the lateral shear failure of the mixes. The gyratory stability test results indicate the stability of the aggregate structure of the mixes.

Dynamic Modulus and Flow Number Tests

The research team conducted the dynamic modulus tests in accordance with *AASHTO T 342-11,Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures*.(59) The temperatures used for the dynamic modulus tests were 40°F, 70°F, 100°F, and 130°F. At each temperature, the researchers applied 6 different loading frequencies: 25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, and 0.1 Hz. After short-term aging for 16 hours at 140°F, the researchers fabricated the specimens by compacting the loose mixes in a gyratory compactor to a target height of 6.7 inches and 5.9 inches in diameter. After compaction, the researchers cored and trimmed the specimens to 5.9 inches in height and 4 inches in diameter with air void levels of 7 ± 0.5 percent. The researchers used an Asphalt Mixture Performance Tester (AMPT) to test the prepared samples. They fabricated and tested a total of three replicates for each mixture. After obtaining the raw data, the researchers averaged the dynamic modulus values of all three samples at each combination of temperature and frequency sets and calculated the standard deviation and COV for each temperature and frequency.

The flow number test typically is used after dynamic modulus testing to measure the rutting potential of asphalt concrete mixtures. As shown in Figure 11, the flow number is the number of load repetitions when the permanent deformation rate reaches to the minimum. The research team conducted flow number tests using a loading cycle of 1.0-second in duration, which consisted of a 0.1-second haversine load pulse followed by a 0.9-second rest at a test temperature of 130°F. This protocol is in accordance with *AASHTO TP79-13, Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*.(60) The researchers used UTS005 version 1.33 software to calculate and record the flow points and cycles automatically. The researchers then compared the flow number measured for each mix to the minimum flow number criteria recommended in the NCHRP Report 702 for HMA, as shown in Table 11. (34)

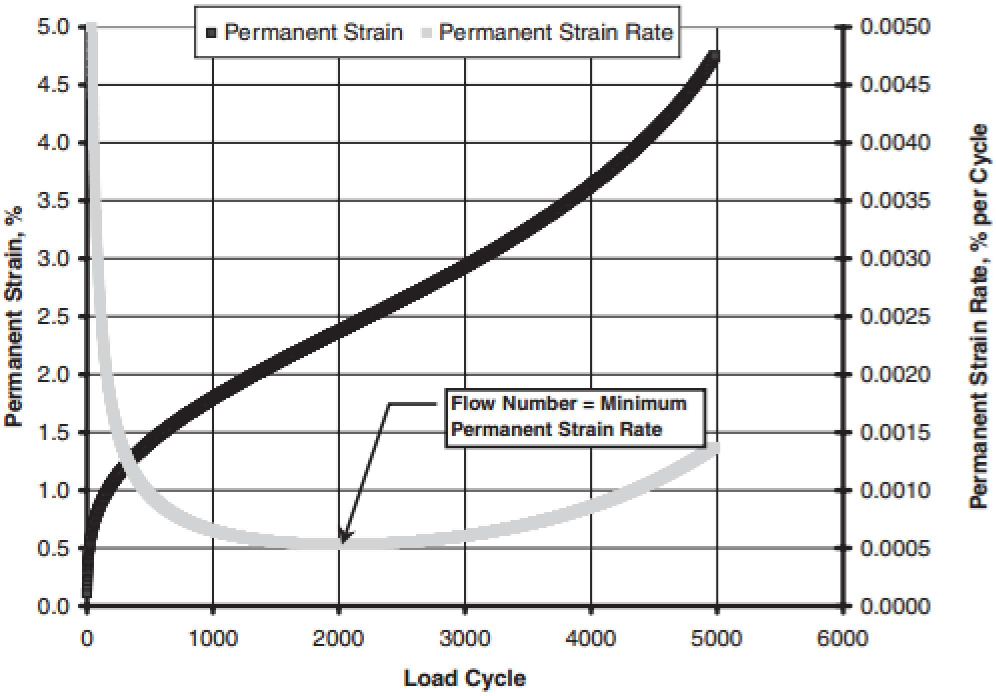


Figure 11. Schematic of Flow Number Test Data(34)

Table 11. Minimum Flow Number Requirements Recommended by NCHRP Report 702(34)

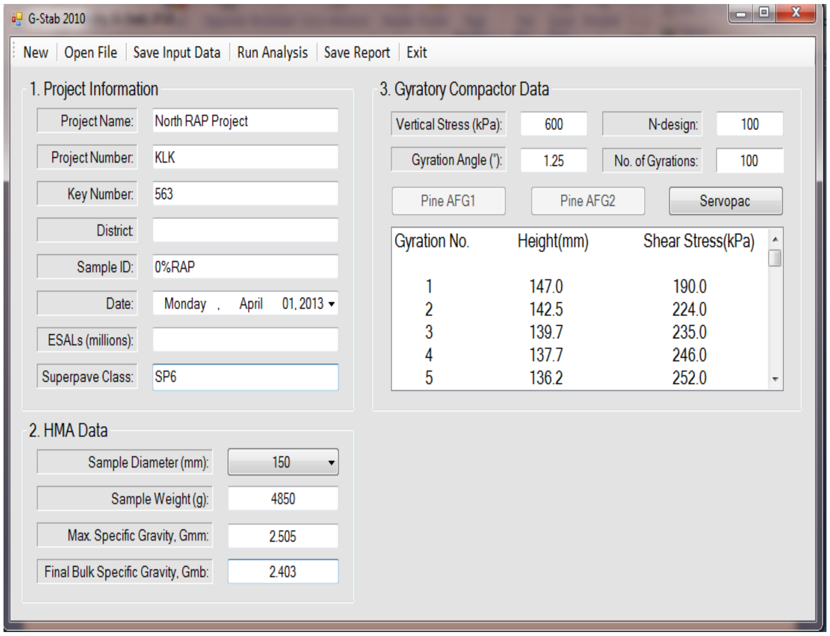
Traffic Level, Million ESALs	Minimum Flow Number, Cycles (HMA)	Minimum Flow Number, Cycles (WMA)
<3	-	-
3 to <10	50	30
10 to <30	190	105
Equal or >30	740	415

Gyratory Stability Tests

The research team determined the gyratory stability of the asphalt mixes to evaluate the stability of the aggregate structures of the mixes. The researchers calculated the gyratory stability values for each mix at 4 ± 0.5 percent air void content. The Servopac Gyratory Compactor, as shown in Figure 12, was set in accordance with the testing procedure that developed in a previous research for ITD. Additional information about gyratory stability testing can be found in the literature.(61)

Figure 12. Servopac Gyratory Compactor and Gyratory Stability Sample after Compaction

Compaction data, such as specimen height, density, and number of gyrations, transferred automatically from the Servopac compactor to a built-in file. Using Visual Basic software, G-STAB, the researchers could easily import and integrate these data into the software to calculate the gyratory stability values.(62) Figures 13 and 14 show the compaction data from a gyratory stability software output file and the gyratory stability results, respectively.



1. Project Information

Project Name:	North RAP Project
Project Number:	KLK
Key Number:	563
District:	
Sample ID:	0%RAP
Date:	Monday , April 01, 2013
ESALs (millions):	
Superpave Class:	SP6

2. HMA Data

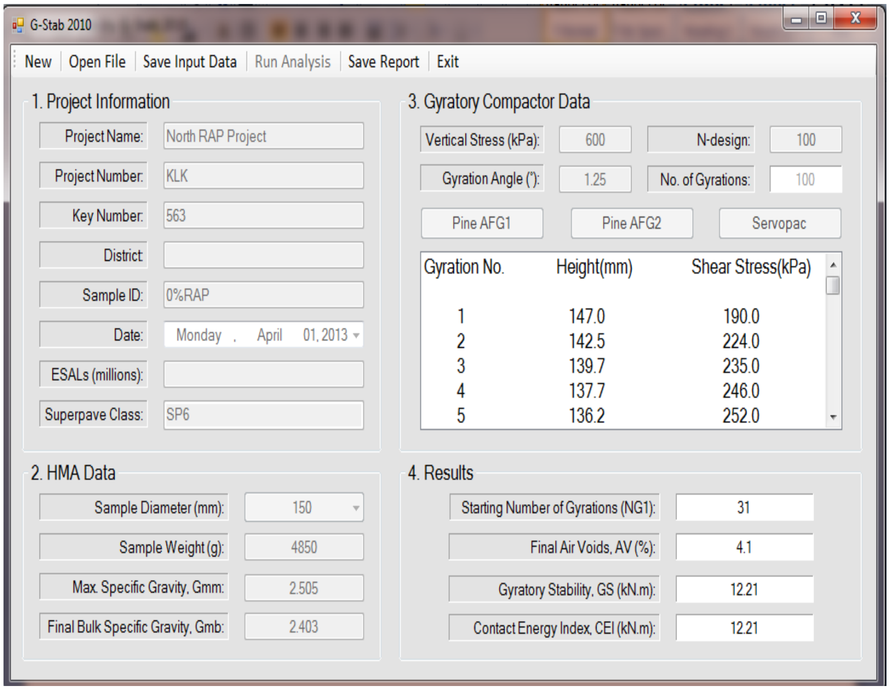
Sample Diameter (mm):	150
Sample Weight (g):	4850
Max. Specific Gravity, Gmm:	2.505
Final Bulk Specific Gravity, Gmb:	2.403

3. Gyratory Compactor Data

Vertical Stress (kPa):	600	N-design:	100
Gyration Angle (°):	1.25	No. of Gyrations:	100

Gyration No.	Height(mm)	Shear Stress(kPa)
1	147.0	190.0
2	142.5	224.0
3	139.7	235.0
4	137.7	246.0
5	136.2	252.0

Figure 13. Project Information Window When All Data Entries are Complete



1. Project Information

Project Name: North RAP Project
Project Number: KLK
Key Number: 563
District:
Sample ID: 0%RAP
Date: Monday , April 01, 2013
ESALs (millions):
Superpave Class: SP6

2. HMA Data

Sample Diameter (mm): 150
Sample Weight (g): 4850
Max. Specific Gravity, Gmm: 2.505
Final Bulk Specific Gravity, Gmb: 2.403

3. Gyratory Compactor Data

Vertical Stress (kPa): 600
N-design: 100
Gyration Angle (°): 1.25
No. of Gyrations: 100

Gyration No.	Height(mm)	Shear Stress(kPa)
1	147.0	190.0
2	142.5	224.0
3	139.7	235.0
4	137.7	246.0
5	136.2	252.0

4. Results

Starting Number of Gyrations (NG1): 31
Final Air Voids, AV (%): 4.1
Gyratory Stability, GS (kN.m): 12.21
Contact Energy Index, CEI (kN.m): 12.21

Figure 14. Project Information Window When Analysis is Complete

Fatigue Cracking Resistance

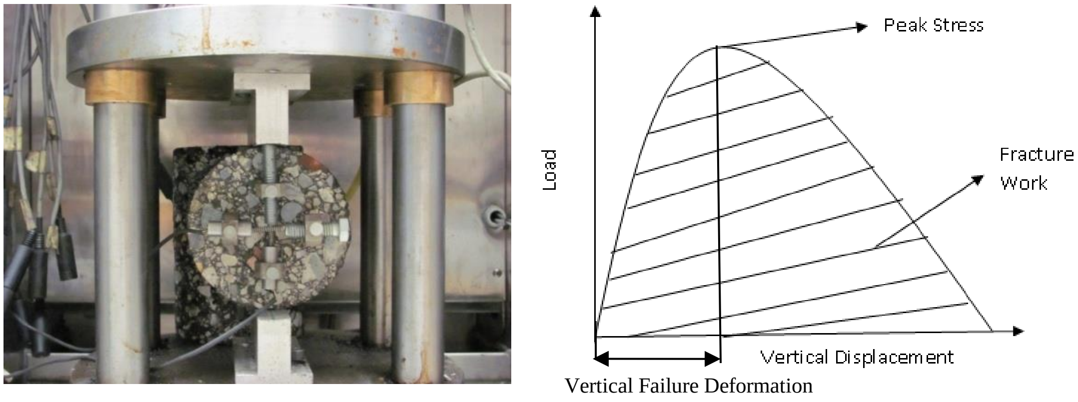
The team subjected the samples used for the fatigue tests to long-term aging. The preparation process for the laboratory fatigue test samples is as follows:

> **Step 1:** Heat the virgin aggregate at the mixing temperature for three hours and blend the virgin aggregate with RAP for mixes that contain RAP. Then, heat the virgin aggregate and RAP together for another two hours and mix with the virgin binder.
>
> **Step 2:** Age the laboratory loose mix at the compaction temperature for 2 hours and short-term age the mix at 140°F for 16 hours followed by 2 hours at the compaction temperature for gyratory compaction.
>
> **Step 3:** Compact the laboratory loose mix to 4.53 inches in height and 6.0 inches in diameter using a gyratory compactor. Cut and core the compacted samples to 4.0 inches in diameter and 1.5 inches in thickness with air voids of 4 ± 0.5 percent. Then, long-term age 4-inch samples at 185°F for 5 days.

Because the plant-produced mixes obtained from 2 field projects already had been aged in an asphalt plant and had been stored approximately one year in a laboratory, the research team heated them at 2.5 hours at the compaction temperature for gyratory compaction, and then followed Step 3 for the long-term aging process.

The research team characterized fatigue cracking resistance using fracture work density and vertical failure deformation data obtained from IDT tests at 68°F to evaluate the mixtures' resistance to bottom-up cracking and top-down cracking, respectively. The indirect tensile test was set up as shown in Figure 15a.(63) The definition of *fracture work density* is fracture work divided by sample volume, and *fracture work* is the entire area under the load versus the vertical displacement curve, as shown in Figure 15b. The definition of *vertical failure deformation* is the vertical displacement under the peak load, which indicates the ductility of the mix to resist top-down cracking, as shown also in Figure 15b.

The research team used a servo-hydraulic Geotechnical Consulting Testing System (GCTS) with an environmental chamber to test the samples. The researchers mounted four linear variable differential transformers (LVDTs) on the front and back of each sample to measure the horizontal and vertical deformations during the tests. Once they attached the LVDTs, the researchers placed the specimen in the loading apparatus, which consisted of top and bottom plates with loading strips of the proper curvature to load the specimens, as shown in Figure 15. The team performed fatigue tests at 68°F with a deformation rate of 2 inches per minute using the GCTS ram. The machine continued the deformation until the load on the sample achieved a value close to zero. The team tested three replicates for each type of mix and then calculated the average values and COVs.



(a) (b)

Figure 15. Indirect Tensile Test (a) Indirect Tensile Test Set-up and (b) Load-Displacement Curve of Indirect Tensile Test

Low Temperature Thermal Cracking Resistance

The research team conducted creep compliance and IDT strength tests at 14°F to characterize the low temperature properties of mixtures in accordance with *AASHTO T322-07(2011), Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*.(64) The team conducted a nondestructive creep compliance test for each sample at -4°F, 14°F, and 32°F with a constant load duration of 100 seconds. The team then carried out IDT strength tests at 14°F at a displacement rate of 0.1 inch per minute. IDT strength test continued to deform the sample until the load on the sample reached a value of zero and the specimen completely split apart. The researchers used the creep compliance and IDT strength values in MEPDG program to predict the mixtures' thermal cracking performance (presented in Chapter 5). The researchers then calculated the fracture work density values of the mixtures from IDT strength test results at 14°F to compare the resistance to thermal cracking of mixtures with different percentages of RAP.

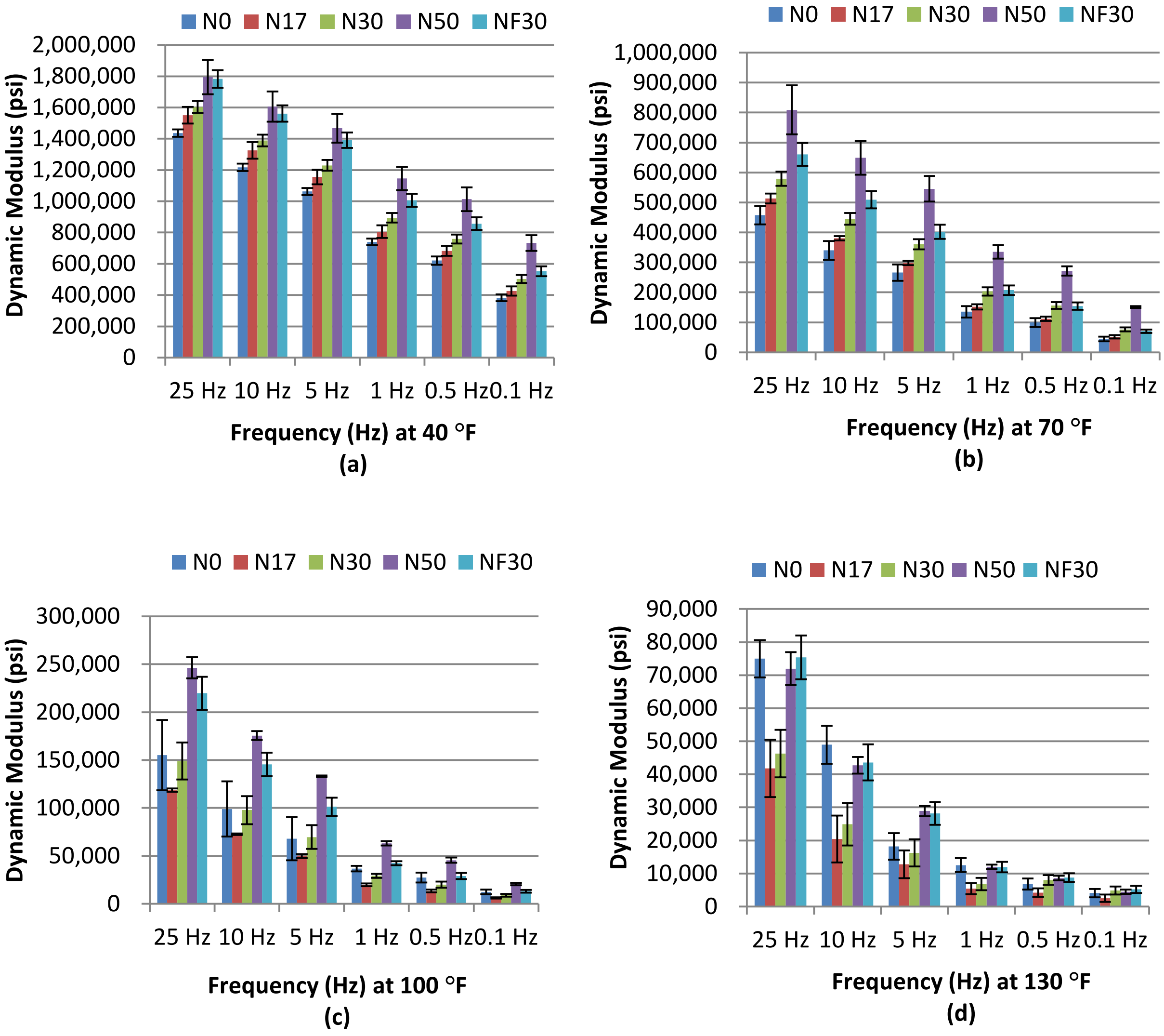
Because the resistance to low temperature thermal cracking reflects the long-term performance of the mixtures, the conditioning of the samples used for the thermal cracking tests was the same as the procedure for IDT fatigue tests.

Results and Discussion

North RAP Mixes

The research team determined dynamic modulus values as inputs to MEPDG program for performance predictions. Figure 16 shows the measured dynamic modulus values at different temperatures. Table 15 in Appendix B presents details regarding the dynamic modulus values for all the samples. At 40°F and 70°F, the stiffness values of the North mixes are seen to increase as RAP percentage increases, even though the research team used binder grade bumping and followed the blending chart to adjust the grade of the virgin binders. However, at 100°F, the dynamic modulus values of N0 are higher than those of N17 and close to those of N30 and NF30. At 130°F, N0, N50, and NF30 exhibit higher dynamic modulus values than N30 and N17. N17 mixture has the lowest dynamic modulus values.

As indicated in Table 11 for the minimum flow numbers recommended by NCHRP Report 702, the recommended minimum flow number, based on ESALs, for the North mixes is 190, as indicated by the red line in Figure 17. Figure 17 shows that all the mixes surpassed this number, which indicates that all the mixtures have reasonable resistance to lateral shear failure. As RAP percentage increased, the flow number increased. The North mix with 50 percent RAP has the highest flow number, followed by N30 and NF30. N17 is comparable to the control mix in terms of flow number. The fact that N30 has a higher flow number than N17 indicates that reducing binder grade did not offset the stiffening effects of inclusion of RAP in the mixes, and that the degree of blending may not complete. The high flow number of N50 may be attributed to the use of PG 52-34 virgin binder, instead of PG 40-34 virgin binder recommended by the blending chart, as well as incomplete blending between RAP binder and virgin binder. Table 16 in Appendix B presents details regarding the flow number testing. Table 17 in Appendix B presents the statistical analysis of the results, which shows significant differences among the mixes. N50 showed the highest significant difference compared to the other mixes.



(a)

(b)

(c)

(d)

Figure 16. Dynamic Modulus (psi) of North Mixes at (a) 40°F, (b) 70°F, (c) 100°F, and (d) 130°F

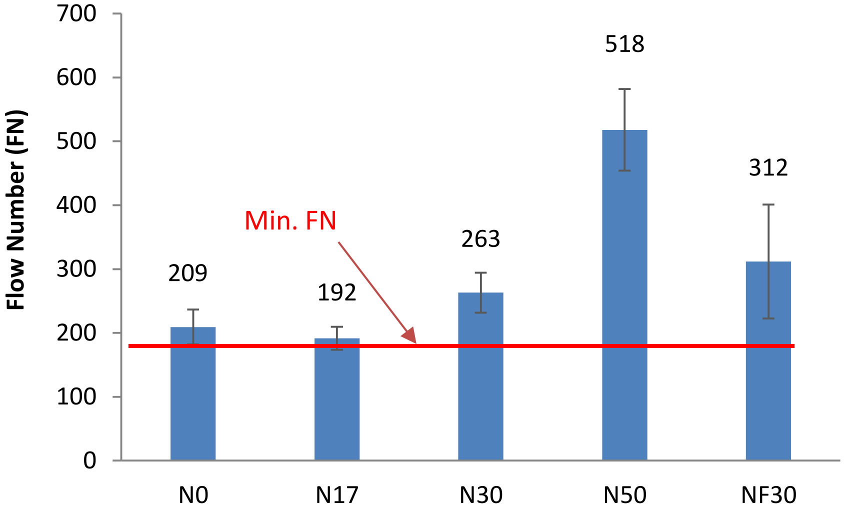


Figure 17. Average Flow Numbers of North Mixes

Figure 18 presents the gyratory stability test results for the North mixes. Table 18 in Appendix B presents detailed tests results. A comparison of the control mix and RAP mixes shows that RAP mixes have comparable or slightly higher gyratory stability values than the control mix. N17 has the highest gyratory stability value, followed by N50, N30, and NF30. Although the statistical analysis presented in Table 19 shows significant differences among some of mixes due to the high repeatability of the gyratory stability tests, the gyratory stability values of the North mixes are very close to each other, as indicated in Figure 18. This finding is reasonable, because the North mixes have identical aggregate gradations and gyratory stability is an indicator to aggregate stability.

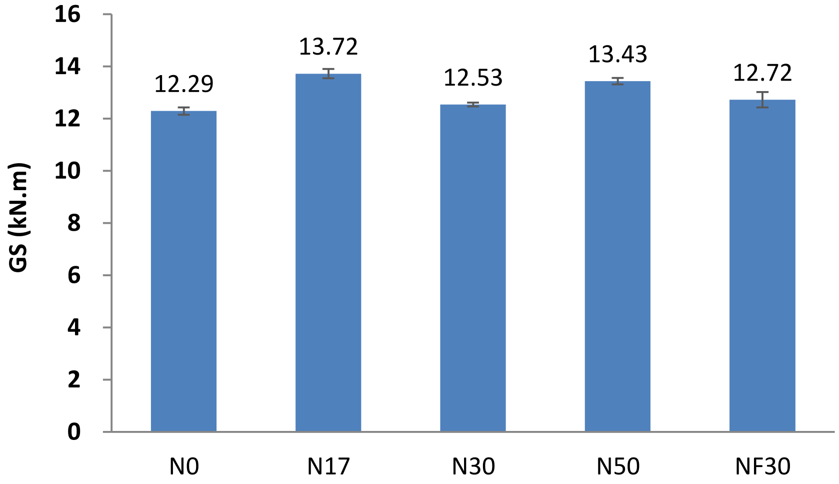
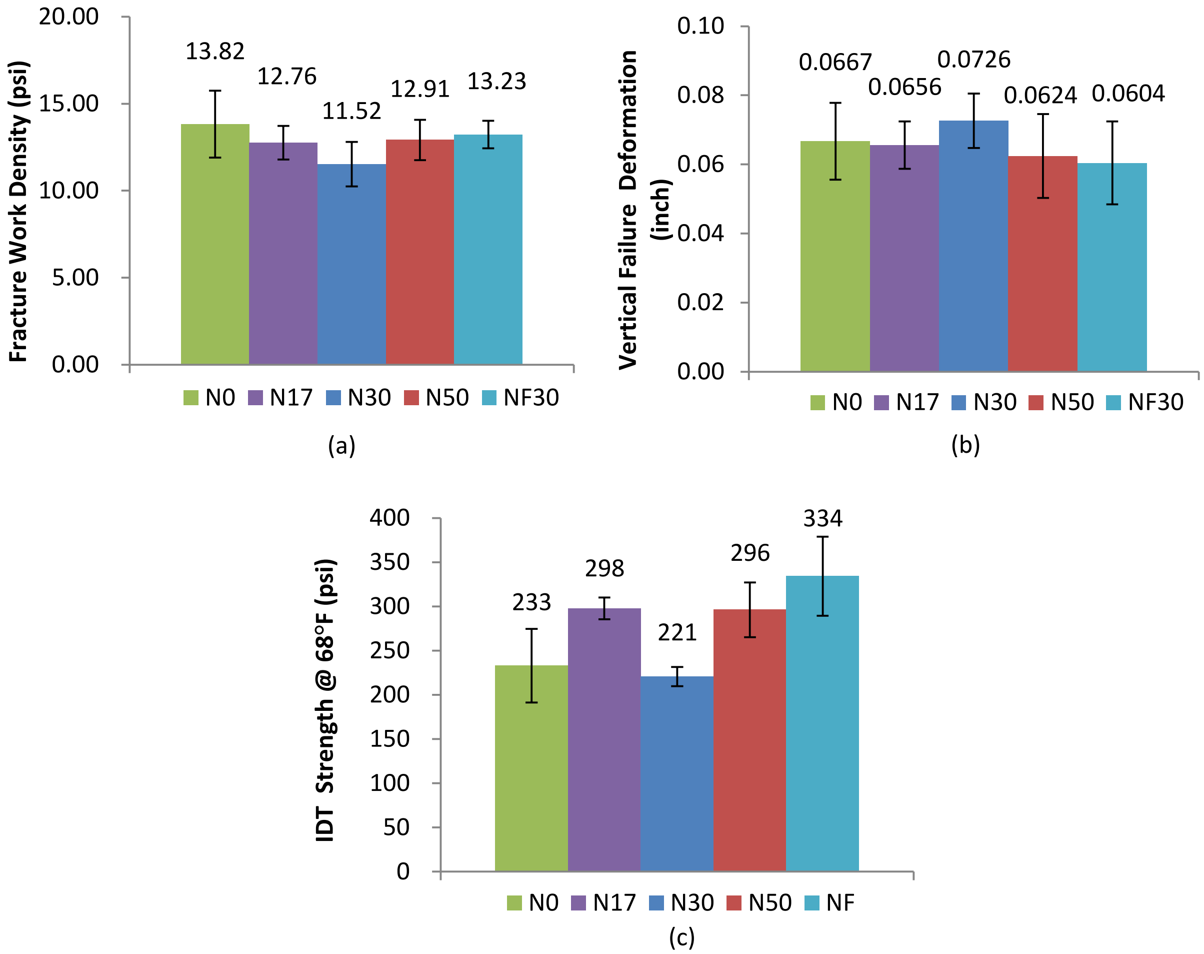


Figure 18. Gyratory Stability Values of North Mixes

Figure 19 and Tables 20, 21, and 22 show the results for fracture work density, vertical failure deformation, and IDT strength at 68°F for the North mixes with different percentages of RAP, as obtained from IDT test at 68°F. ANOVA provided multiple comparisons between the results for fracture work density and vertical failure deformation of mixes at the level of significance of 0.05. Table 23 in Appendix B presents the statistical analysis results. Both the bar charts and statistical analysis show no significant differences in terms of fracture work density and vertical failure deformation among the North mixes with different percentages of RAP, which indicates that all of the North mixes have comparable resistance to bottom-up and top-down fatigue cracking. As mentioned before, although the blending of RAP binder and virgin binder may not be thorough, this incomplete blending does not seem to have affected the fatigue cracking resistance of the North RAP mixes.



(a)

(b)

(c)

Figure 19. North Mixes: (a) Fracture Work Density, (b) Vertical Failure Deformation, and (c) IDT Strength at 68°F

Figure 20 and Table 24 show the results of the low temperature thermal cracking tests of the North mixes in terms of fracture work density. Tables 25 and 26 in Appendix B present the complete results of IDT strength and creep compliance tests. The researchers also present these results for the performance predictions by MEPDG program in Chapter 5. ANOVA provided multiple comparisons of the North mixtures in terms of fracture work density values obtained from IDT tests at 14°F and at a level of significance of 0.05, as shown in Table 27 in Appendix B.

The results show that the North mix without RAP (N0) has a higher fracture work density value than N17, N50, and NF30, indicating that North RAP materials incorporated into the North mixes affect the mixtures' resistance to thermal cracking. However, statistically, the fracture work density values of N0 and N30 are comparable, without significant difference at a level of 0.05. One reason for the improved resistance to thermal cracking of N30 is that it used softer virgin binder (PG 52-34) than the target PG 58-28 binder.

Overall, the binder grade adjustment seems to have worked well with regard to fatigue cracking resistance at the intermediate temperature for the North RAP mixes. However, the fact that the rutting resistance at the high temperature increased as a result of an increase in RAP percentage and that the low temperature cracking resistance was compromised as RAP percentage increased indicates that the binder blending was not complete. That is, the binder grade adjustment did not work well for the low temperature cracking resistance of North RAP mixes.

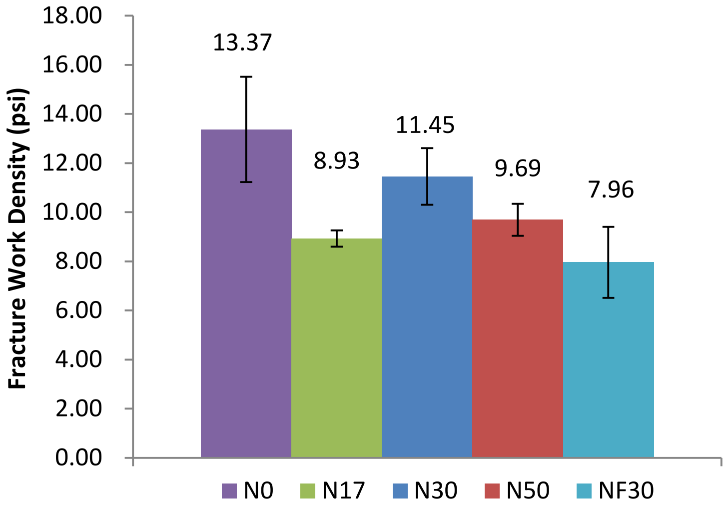


Figure 20. Fracture Work Density of North Mixes from IDT Strength Test at 14°F

South RAP Mixes

Figure 21 shows the measured dynamic modulus values at different temperatures, and Table 28 in Appendix B shows the detailed dynamic modulus values. It is interesting to note that S26 and SF26 have lower dynamic modulus values than other mixes at a temperature of 40°F, 70°F, and 100°F, respectively, and have higher dynamic modulus values at the temperature of 130°F.

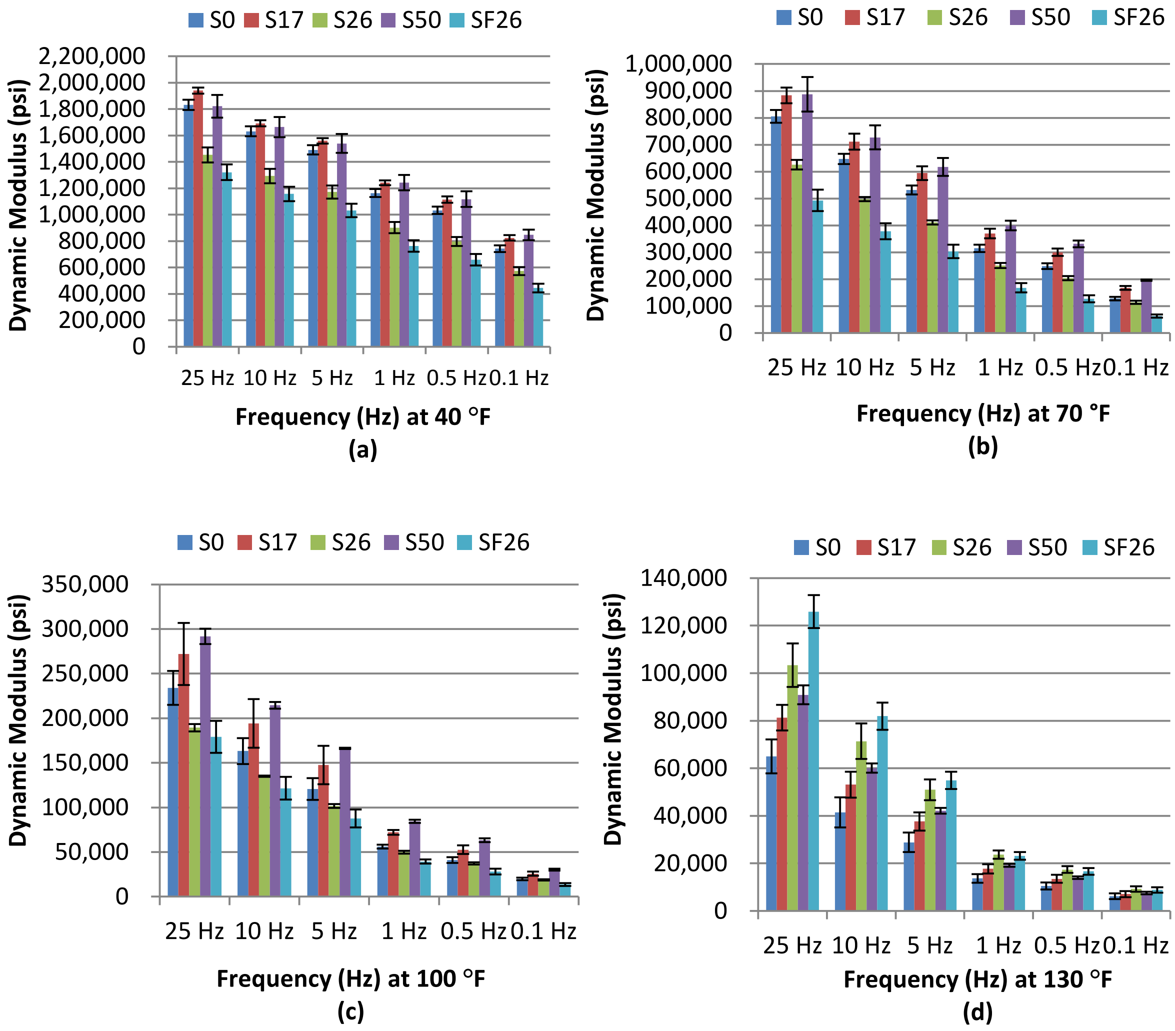


Figure 21. Dynamic Modulus (psi) of South Mixes at (a) 40°F, (b) 70°F, (c) 100°F, and (d) 130°F

As indicated in Table 11, the minimum flow number recommended by NCHRP Report 702 for the South mixes is 50.(34) Figure 22 and Table 29 in Appendix B show that all the mixes surpassed this number, which indicates that all the South mixtures have a strong resistance to rutting. Based on the statistical analysis presented in Table 30 in Appendix B, S26, S50, and SF26 have higher flow number values than S0 and S17. The 17 percent RAP mix has a comparable flow number to that of the control mix, S0. Again, the fact that S26, SF26, and S50 still have higher flow numbers than S0 and S17 indicates that the grade bumping and the use of the blending chart did not offset the stiffening effects of RAP and that the blending of RAP binder and virgin binder may not have been thorough.

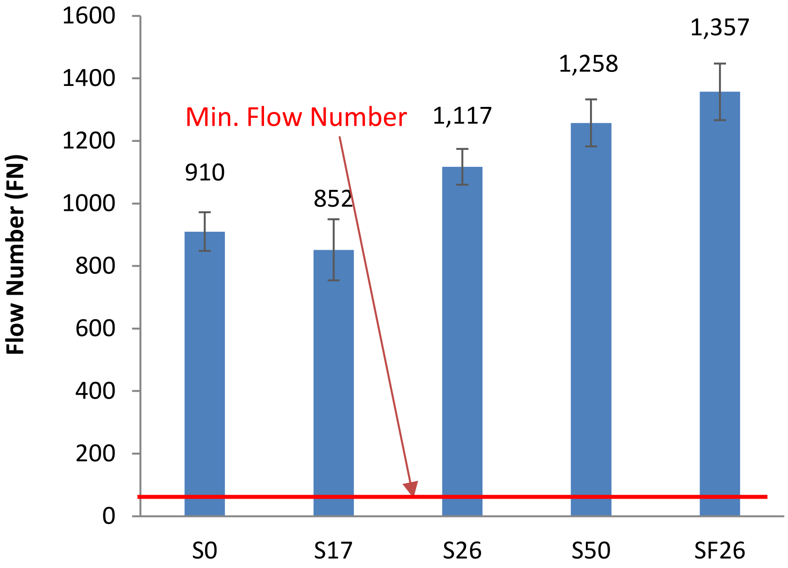


Figure 22. Average Flow Numbers of South Mixes

Figure 23 as well as Table 31 in Appendix B present the gyratory stability values of the South mixes. The South mixes show comparable gyratory stability values to each other. This outcome is reasonable because the final blended aggregate gradations of the South mixes are controlled to be the same. The statistical analysis presented in Table 32 shows a slight difference among some of RAP mixes.

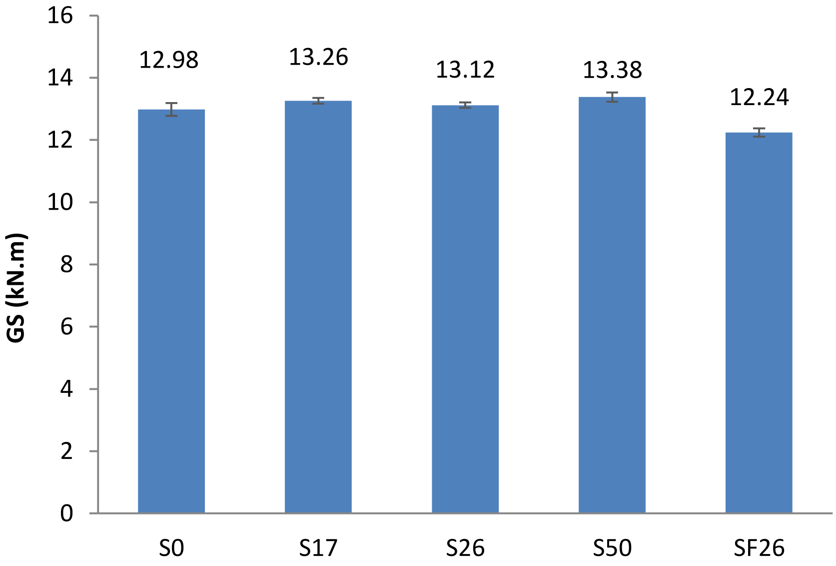


Figure 23. Gyratory Stability Values of South Mixes

Figure 24 and Tables 33, 34, and 35 in Appendix B show the results for fracture work density, vertical failure deformation, and IDT strength at 68°F for the South mixes with different percentages of RAP, as obtained from IDT test at 68°F. ANOVA provided multiple comparisons among mixes at the level of significance of 0.05. Table 36 in Appendix B presents the detailed statistical results.

For the fracture work density results of the South mixes, based on ANOVA analysis, S0 performed identically with S17, but was significantly better than S26, S50, and SF26. In terms of vertical failure deformation, S0 and S17 performed identically, and S17 was significantly better than S26, S50, and SF26. Mixes with high percentages of RAP, i.e., S26, S50, and SF26, exhibited similar fracture work density and vertical failure deformation values. Recall that for the North mixes, no statistically significant difference in fracture work density and vertical failure deformation was evident among the different mixes. A possible explanation is that when the soft virgin binder is used, the use of virgin binder for South mixes may have changed from polymer modified asphalt (e.g. PG70-28) to possibly unmodified (or less modified) binder (e.g. PG 58-34) which could compromise the fatigue performance, while this is not the case for North mixes.

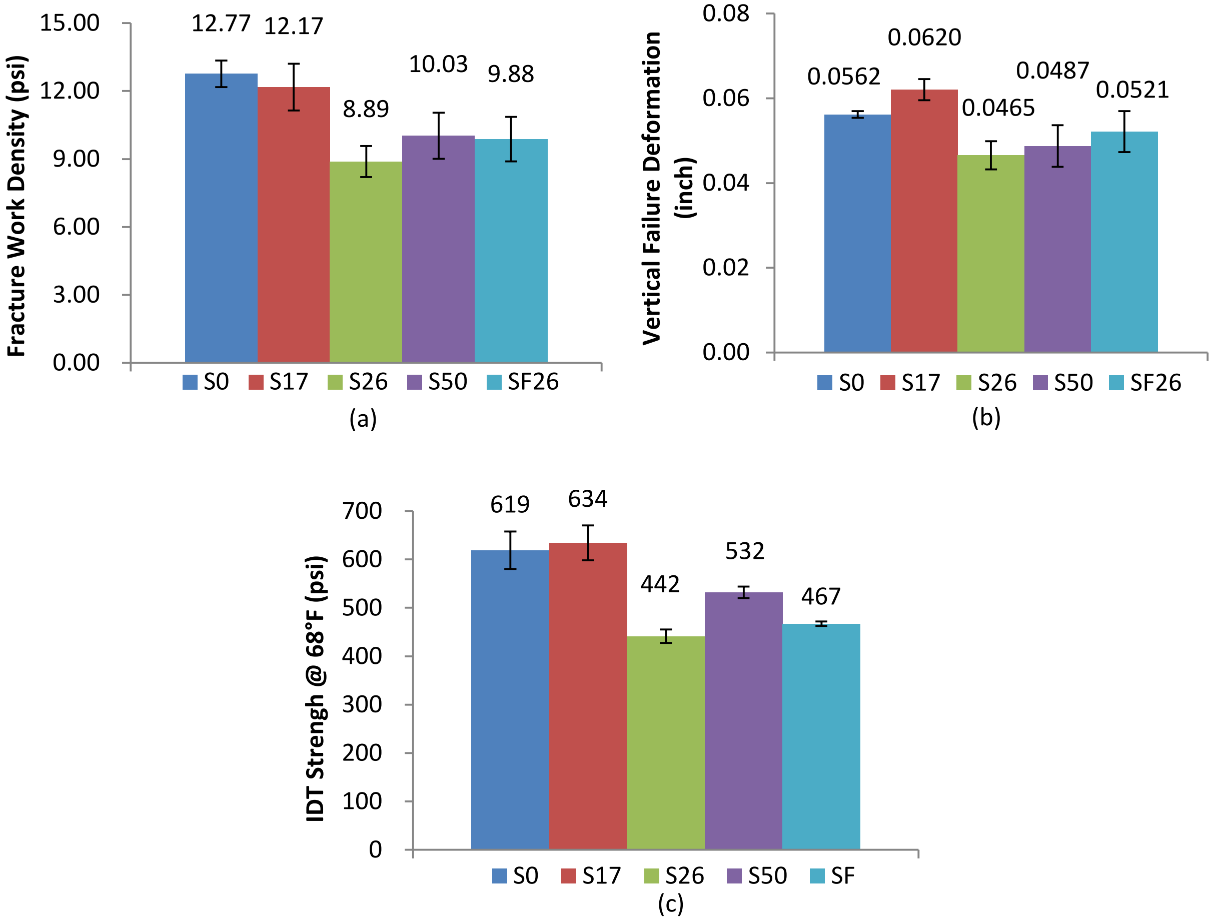


Figure 24. South Mixes: (a) Fracture Work Density, (b) Vertical Failure Deformation, and (c) IDT Strength at 68°F

Figure 25 as well as Table 37 in Appendix B show the results of the low temperature thermal cracking tests of the South mixes in terms of fracture work density. Tables 38 and 39 in Appendix B present IDT strength and creep compliance results; these results were used as inputs to AASHTOWare Pavement ME Design to predict pavement performance. ANOVA provided multiple comparisons of the South mixtures for fracture work density as obtained from IDT strength test at 14°F and at a level of significance of 0.05. Table 40 in Appendix B presents the detailed analysis results. Based on the fracture work density results of the South mixes, S0, S17, S50 and SF26 have similar fracture work density values to resist thermal cracking, and these values are higher than those of S26. For S50, the use of PG 58-34, instead of PG 58-40 as per the blending chart, may have helped to improve the thermal cracking resistance, considering that the blending between RAP binder and virgin binder was not complete.

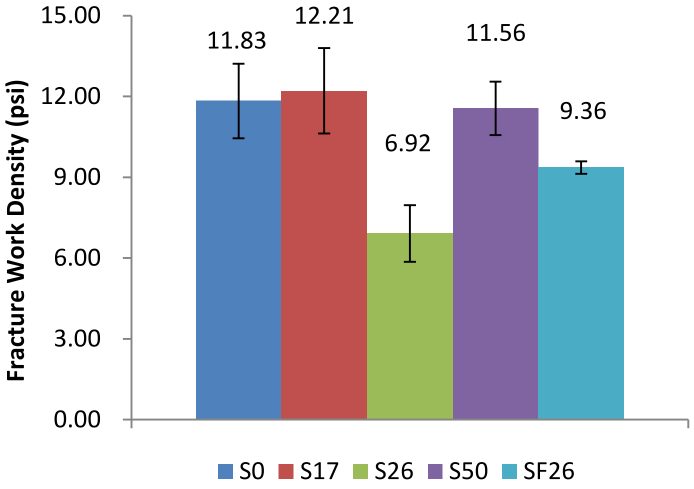


Figure 25. Fracture Work Density of South Mixes from IDT Strength Test at 14°F

Summary of Test Results

Based on the test results, it can be seen that the mixtures' rutting resistance to lateral shear failure, indicated by the flow number, increased as RAP percentage increased. RAP mixture aggregate structure stability for both the North and South mixes, as indicated by the gyratory stability values, was comparable to or slightly better than that of the control mix. Overall, the rutting resistance of RAP mixes was the same as or better than that of the control mix. This result also indicates that the blending between RAP binder and virgin binder was not complete and that the aged RAP binders helped improve the rutting resistance of the mixes.

In terms of fatigue cracking resistance, all of the North mixes performed comparably in terms of both bottom-up and top-down fatigue cracking resistance. However, a comparison among the South mixes showed that the addition of 26 percent or more RAP compromised the resistance to fatigue cracking. The specification of the use of soft binder may change the use of polymer modified binder to unmodified (or less modified) binder which compromises the performance, such as the case of fatigue cracking for South RAP mixes.

In addition, the use of virgin binder PGs that were higher than the very soft binder PGs based on the blending chart for the high RAP mixes (N50 and S50) did not seem to cause any performance problems. In fact, the use of PG 58-34, instead of PG 58-40 as per the blending chart in S50, seemed to be beneficial for pavement performance.

Statistical Analysis

Ideally, cracking performance tests should be included in the mix design to ensure that RAP mixes perform as well as the control mix. However, it is needed to provide guidance to a mix designer to how to achieve designing a RAP mix that perform well, by determining the factors that affect the performance of RAP mix. The test results above indicate that the binder grade bumping and blending chart may not work well, especially for the thermal cracking performance. To determine the significant factors affecting the thermal cracking performance, statistical analysis was conducted based on the test data of North and South mixes, and based on stepwise regression using SPSS program. The factors affecting the low temperature material property, fracture work density, were determined as equation shown in Figure 26:

$$FWD_{low}=9.437+0.179P_{RAP}-5.209AV+6.690VMA+1.475PG_{virgin\_low}-0.513PG_{virgin\_high}$$

Where:

FWD_{low} = Fracture work density at low temperature, psi.
P_{RAP} = Percentage of RAP, percent.
AV = Design air void, 4 percent in most cases.
VMA = Void in mineral aggregate, percent.
PG_{virgin_low} = Low temperature grade of virgin binder.
PG_{virgin_high} = High temperature grade of virgin binder.

Figure 26. Prediction of Fracture Work Density of Control Mix at Low Temperature

It is noted that the low temperature PG of RAP binder is not a statistically significant factor for thermal cracking resistance of a RAP mix, which indicates that the thermal cracking performance of a RAP mix is sensitive to low temperature grade of virgin binder, instead of low temperature grade of RAP binder. Figure 27 indicates that the above model is moderately effective in predicting the fracture work density at low temperature.

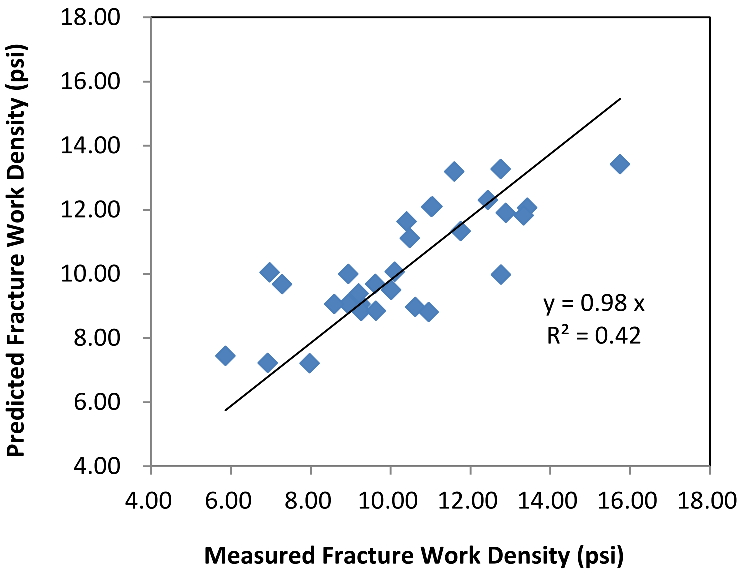


Figure 27. Predicted and Measured Individual Fracture Work Density Relationship

The above model in Figure 26 provides an alternative to design a mix with RAP to achieve the same thermal cracking resistance as that of control mix by selecting proper low temperature PG of virgin binder for a mix with RAP, without the need to conduct performance tests or extract and recover RAP binder. The low temperature PG of virgin binder for a mix with RAP can be determined as Figure 28:

$$PG_{virgin\_low}=(FWD_{low}-9.437-0.179P_{RAP}+5.209AV-6.690VMA+0.513\ PG_{virgin\_high})/1.475$$

Figure 28. Virgin Binder Selection of Low Performance Grade for RAP Mixes

The high temperature grade of virgin binder (PG_{virgin_high}) can be kept at high temperature PG of target PG to avoid the loss or reduction of the degree of polymer modification. A design of RAP mix without performing performance tests or extracting/recovering RAP binder consists of the following steps:

1. Design a control mix without RAP to meet ITD specification with a binder of target PG.

2. Estimate FWD_{low} of control mix, based on Figure 26.

3. Design a RAP mix to meet ITD specification with a binder of PG_{virgin_high} and any low temperature PG, because the low temperature PG of binder does not significantly affect the volumetrics of a mix. Keep the high temperature PG of target binder for the RAP mix.

4. Determine the low temperature PG of virgin binder for RAP mix using Figure 28, based on RAP mix's design air void, VMA, P_{RAP}, FWD_{low} of control mix, and PG_{virgin_high}. I

It is noted that the above model is based on a limited number of mixes and warrants further validation.

Chapter 5
Performance Prediction

AASHTOWare Pavement ME Design Input Parameters and Their Significance

Chapter 4 presented the laboratory analysis of the material properties of the study mixes containing RAP. However, it is plausible to evaluate the predicted pavement performance in the field of these RAP mixes under actual traffic and climate conditions. The research team employed AASHTOWare Pavement ME Design software to evaluate the performance of flexible pavements. The purpose of this chapter is to evaluate the effects of RAP on pavement performance based on the identified properties of the mixes and AASHTOWare Pavement ME Design analysis.

Project Locations

The North RAP project is located between Garwood and Sagle at Northern Idaho and starts at the junction of state highway 53 and Ohio Match Road in Kootenai County, as shown in Figure 29. The project consists of a reconstruction section on US-95 from mile point (MP) 438.825 to MP 441.164.

Figure 29. North RAP Project Location

The location of the South RAP project is between Wilder and Parma at Southern Idaho. It is a rehabilitation project that consists of 7.87 miles of US-95 from MP 38.432 to MP 46.602, as shown in Figure 30. The purpose of this project is to extend the pavement life and restore the surface of the existing asphalt pavement to avoid more costly repairs at a later date. The condition of the pavement was “poor” to “very poor” with alligator, block, longitudinal, and transverse cracking. Transverse cracking is the most prominent distress. The international roughness index (IRI) values are generally below 100 inch/mile.

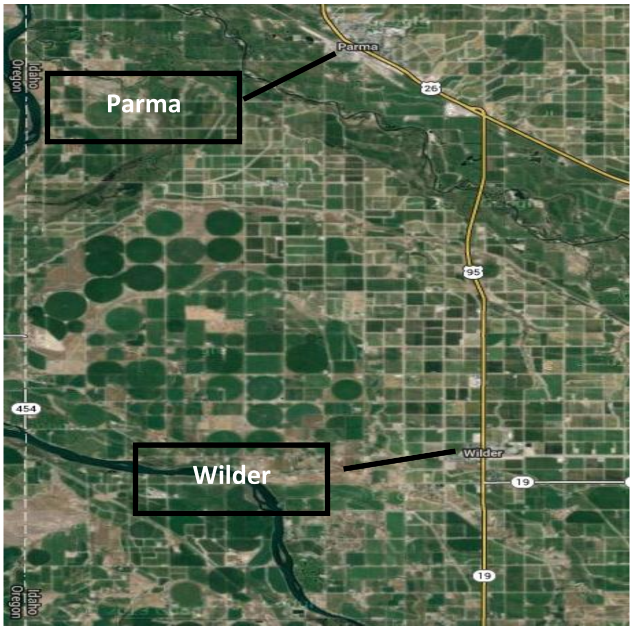


Figure 30. South RAP Project Location

Structure of the Pavements

The pavement structure of the North RAP project consists of 6.6 inches asphalt layer over 10.2 inches of crushed base material. The class of asphalt material is SP5; the ¾-inch maximum size crushed base material has an R-value of 80; and the subgrade soil consists mainly of gravel with silt and sand with an R-value of 60. Figure 43 in Appendix C presents the details.

For the South RAP project, the pavement structure consists of 4 inches asphalt overlay, 1.5 inches existing pavement after milling 4 inches existing asphalt layer, and 7 inches of crushed base material. Figure 44 of Appendix C presents the details. ITD used a falling weight deflectometer to evaluate this roadway section in 2009. Table 12 presents the back calculated layer modulus values of the existing pavement as determined by ITD.

Table 12. Existing Pavement Data of South RAP Project[A]

	Modulus (ksi)		
	Asphalt Layer	**Base**	**Subgrade**
Mean	534	41	16
Standard Deviation	143	22	5
COV (91 tests)	27%	53%	31%

[A] Source: ITD Project Key 11566, Project A0211 (566), ITD Central Lab Reports 109SL0233-236

Analysis

The input data needed for AASHTOWare Pavement ME Design analysis were either provided by ITD or measured directly in the laboratory by the research team. For the predicted pavement performance, the reliability was 90 percent for a design life of 20 years. The performance prediction characteristics for the pavements include fatigue, rutting, thermal cracking, and roughness. The climatic data are based on weather stations that are within approximately 30 miles from the actual project locations. ITD measured AADTT and vehicle class distribution factors, as shown in Figures 45 and 46 and Tables 41 to 48 in Appendix C. As of this writing, the State of Idaho's local calibration factors for AASHTOWare Pavement ME Design are not available. Accordingly, the research team used the nationally calibrated distress models in AASHTOWare Pavement ME Design software. AASHTOWare Pavement ME Design requires complex shear modulus and phase angle data for RTFO-aged binder residue at several temperatures for Level 1 and Level 2 asphalt inputs. The team conducted frequency sweep tests to determine the complex shear modulus and phase angles of the five virgin binders and the extracted RAP binder. The complex shear modulus and phase angles of blended binders were calculated based on the binder replacement ratio. Tables 49 to 63 in Appendix C provide details of the results.

Results and Discussion

Figures 31 through 35 show the predicted rut depths of the asphalt layers, IRI values, and the top-down fatigue cracking, bottom-up fatigue cracking, and thermal cracking results for the North RAP pavements, respectively. For the North US-95 project, the predicted rut depths of the asphalt layers after 20 years, shown in Figure 31, indicate that the lowest permanent deformation value is that of N50 asphalt layer, which is almost the same value as that of N0 asphalt layer. The red horizontal line is the design-life distress threshold used in AASHTOWare Pavement ME Design. The highest rut depth value is that of N17 asphalt layer, followed by that of N30 asphalt layer. This outcome is due to the fact that the rutting model for asphalt layers in AASHTOWare Pavement ME Design is based on the dynamic modulus. At high temperatures, N17 and N30, as shown in Figure 16, have lower dynamic modulus values than other mixes; these values indicate higher values of predicted rutting for N17 and N30. Figure 32 shows no significant difference in predicted IRI values for pavements with different RAP percentages. Figures 33 and 34 present the predicted top-down and bottom-up fatigue cracking results, respectively. Similar to the rutting results, N0 and N50 have the lower top-down fatigue cracking and bottom-up fatigue cracking values, and N17 and N30 have the higher values. Again, these outcomes are due to the fact that the top-down and bottom-up fatigue cracking models in AASHTOWare Pavement ME Design are based on the dynamic modulus. High modulus values of an asphalt mix lead to less fatigue cracking. N17 and NF30 show poor resistance to thermal cracking compared to the other mixes, as shown in Figure 35. This result may be due to the low m-values of the creep compliance (which describes the ability to relieve stress), which is similar to the m-values for the creep stiffness of binder in Superpave binder specifications, as shown in Table 26. In AASHTOWare Pavement ME Design, the thermal cracking model is based on IDT strength, creep compliance, and the slope of the creep compliance mastercurve.

Overall, the predicted performance follows the material properties measured in the laboratory after considering traffic and climate. This outcome makes sense, because the distress models are based on these material properties and the traffic and climate conditions are kept the same for pavements with different RAP percentages. In addition, because this study used nationally calibrated distress models, the absolute values for predicted distresses may not be representative of true pavement performance without the local calibration of these models. However, the ranking of the performance of the different pavements should hold true.

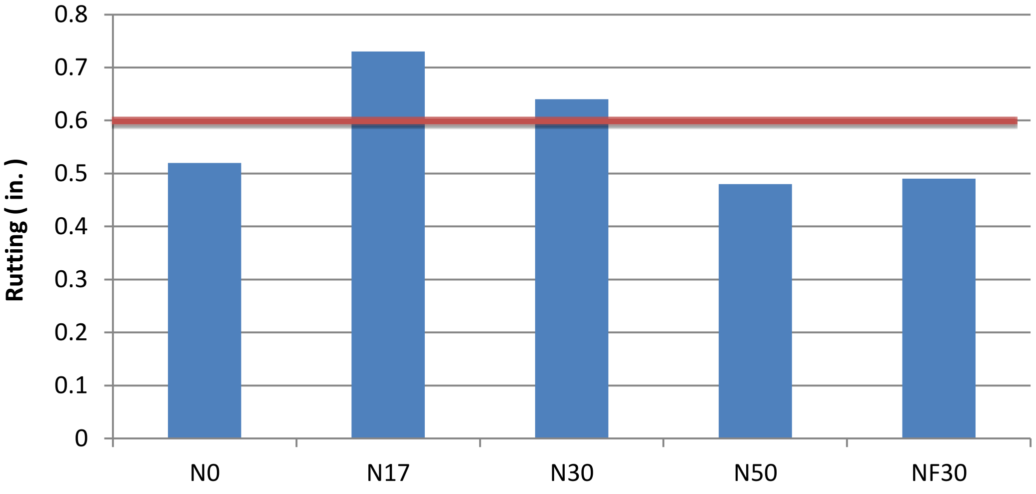


Figure 31. Asphalt Concrete Rutting Values of North RAP Mixes

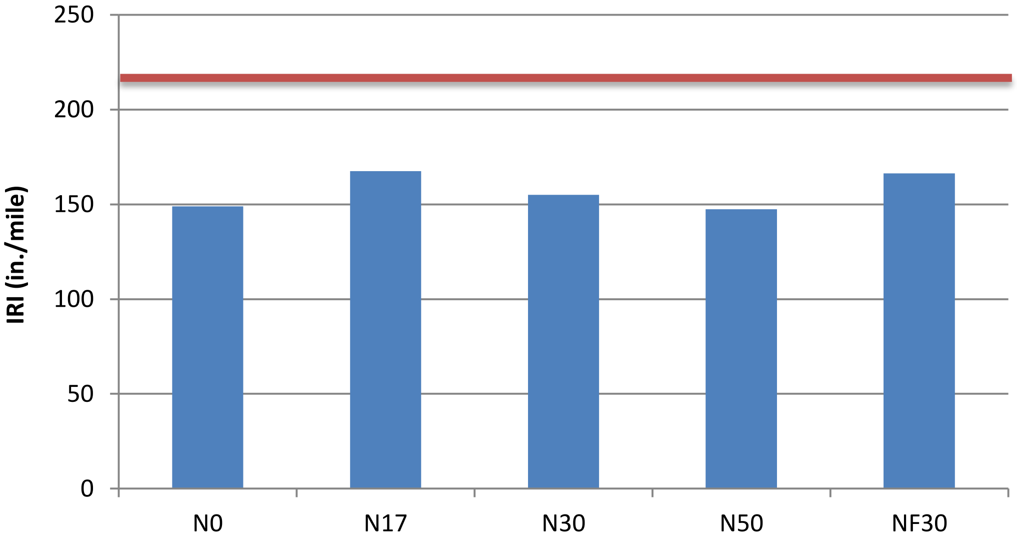


Figure 32. International Roughness Index Values of North RAP Mixes

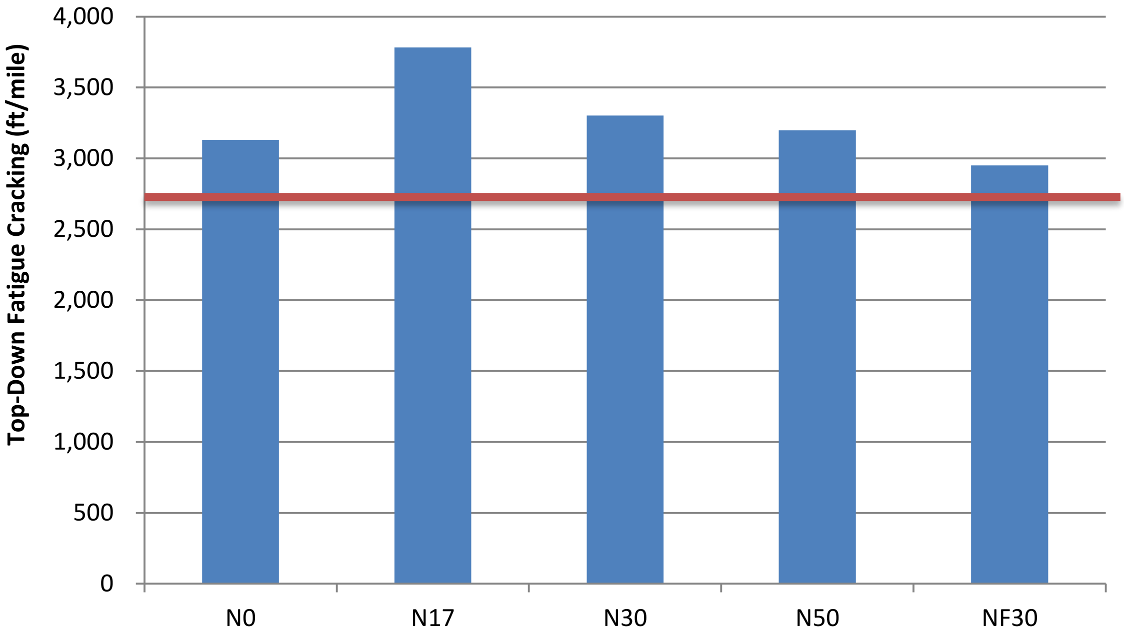


Figure 33. Asphalt Concrete Top-Down Fatigue Cracking of North RAP Mixes

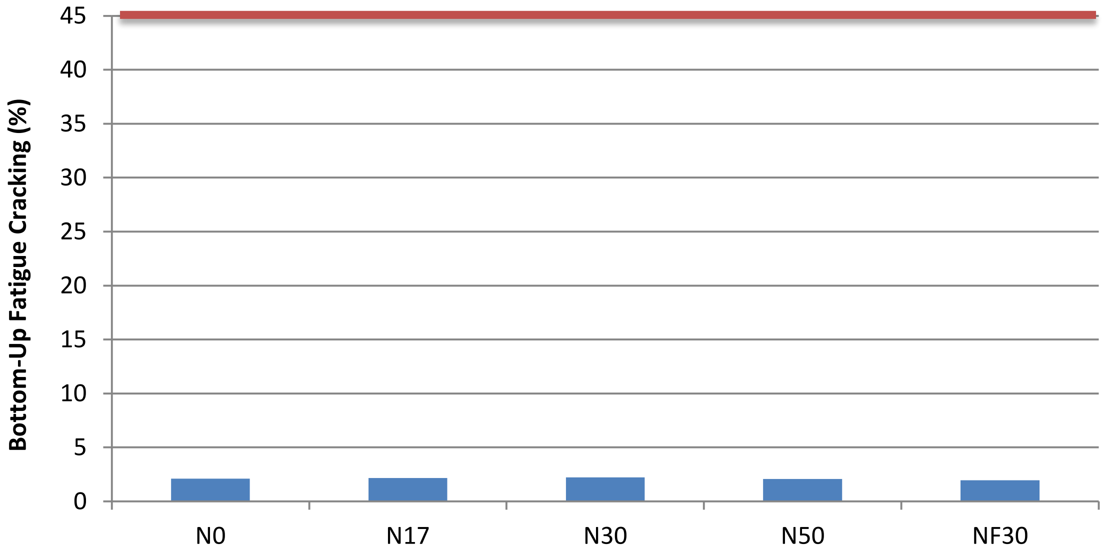


Figure 34. Asphalt Concrete Bottom-Up Fatigue Cracking of North RAP Mixes

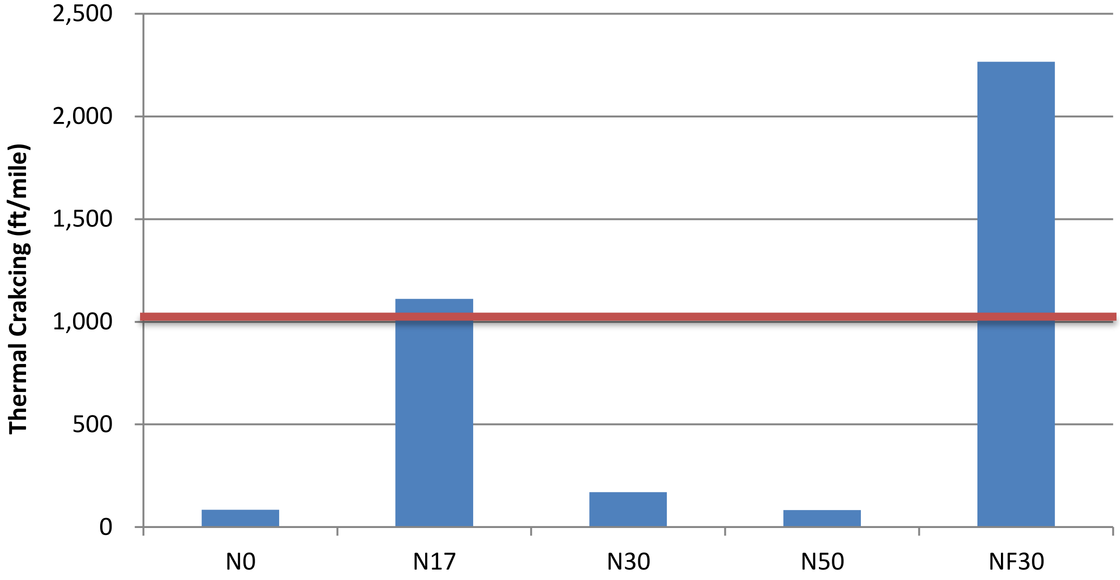


Figure 35. Thermal Cracking of North RAP Mixes

Figures 36 to 40 show the predicted rut depths of the asphalt layers, IRI values, top-down fatigue cracking, bottom-up fatigue cracking, and thermal cracking results for the South pavements, respectively. Generally, the rutting and fatigue cracking performance of all the pavements with different RAP percentages seems to be similar to each other. It is noted that unlike the North mixes, the dynamic modulus values of the South mixes are similar to each other.

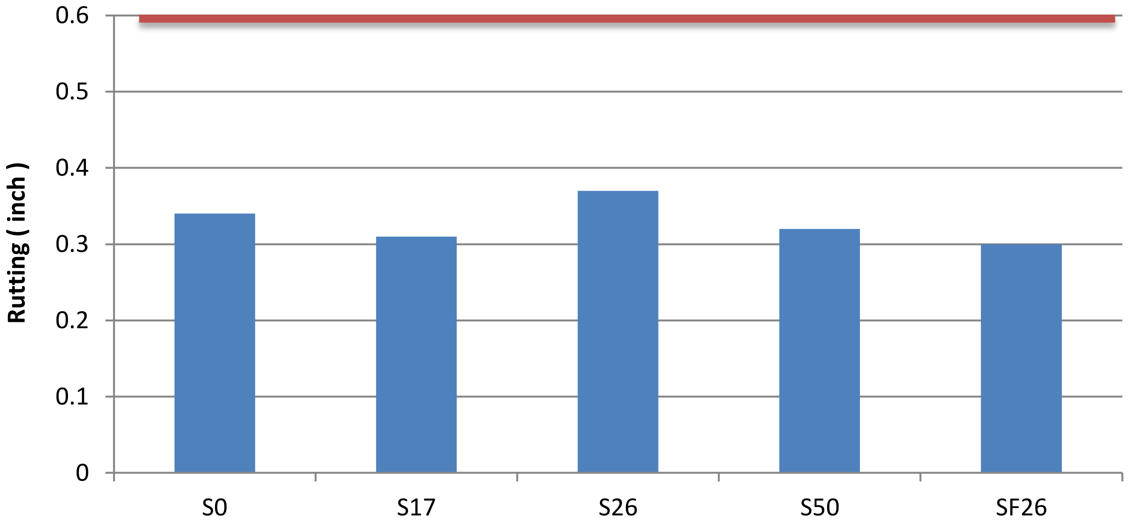


Figure 36. Asphalt Concrete Rutting Values of South RAP Mixes

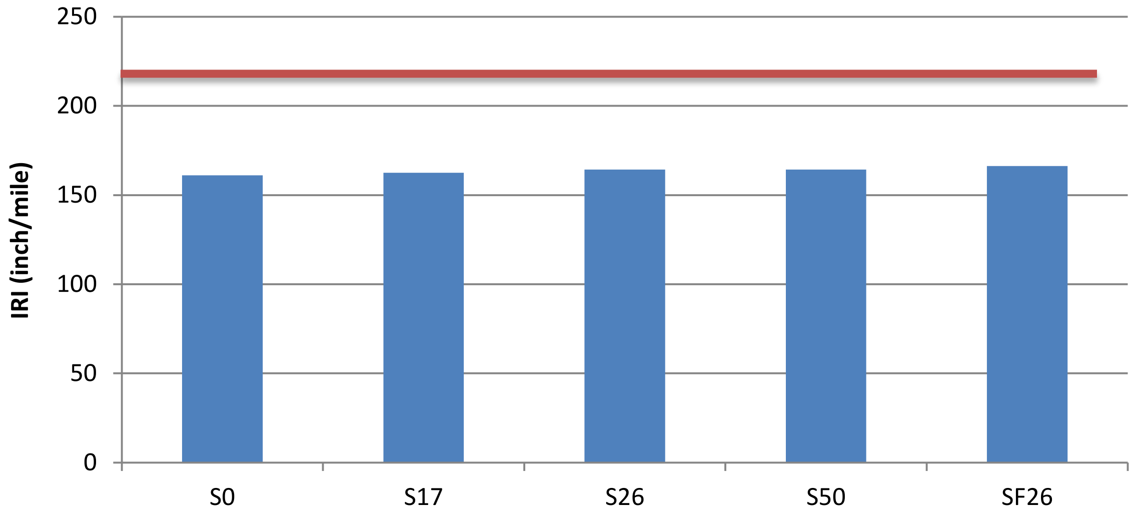


Figure 37. International Roughness Index Values of South RAP Mixes

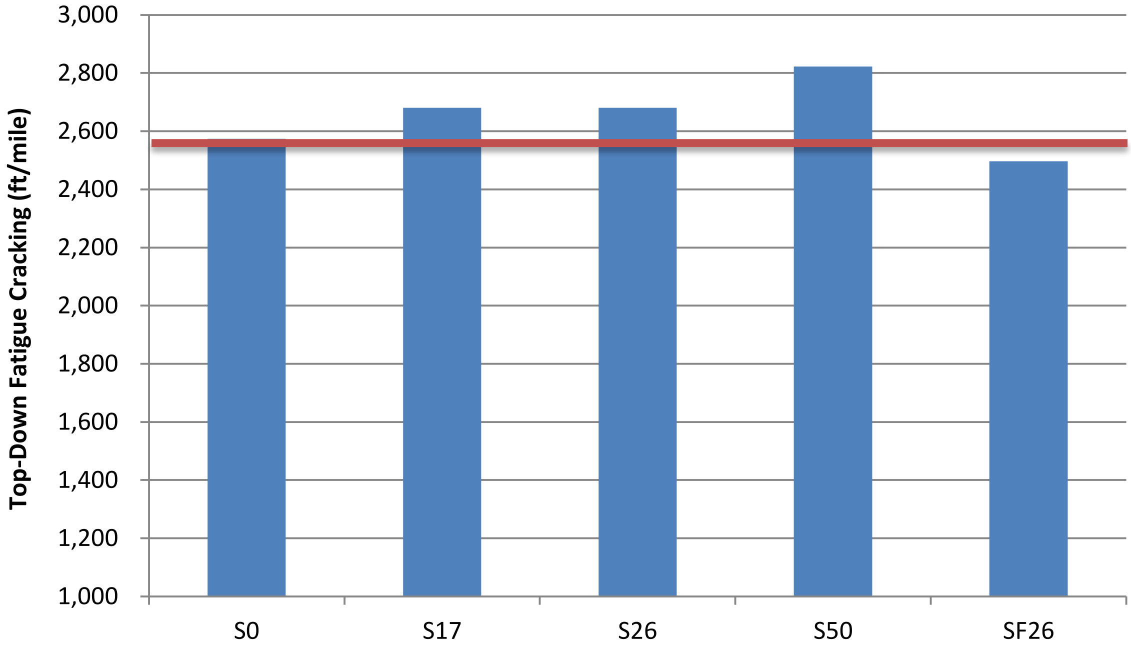


Figure 38. Asphalt Concrete Top-Down Fatigue Cracking of South RAP Mixes

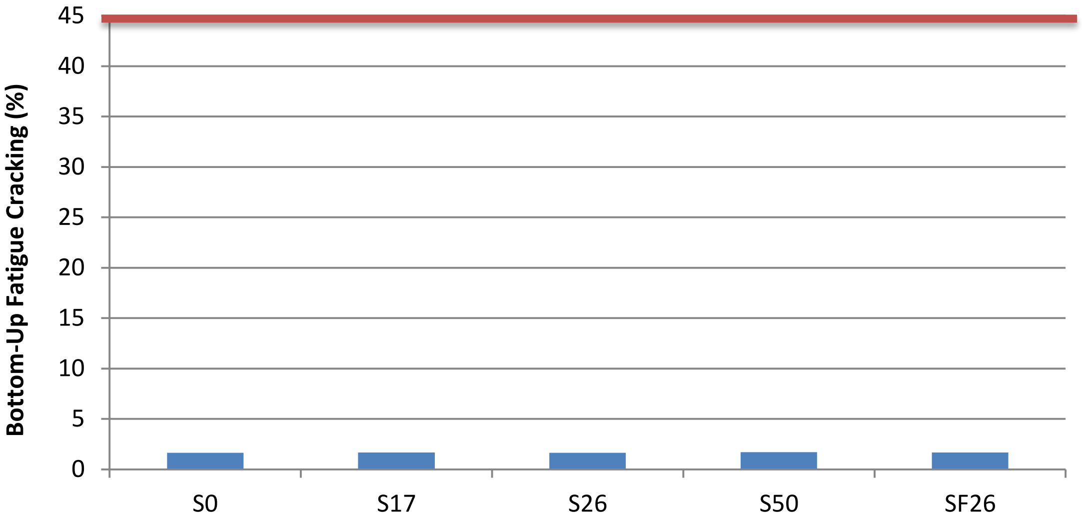


Figure 39. Asphalt Concrete Bottom-Up Fatigue Cracking of South RAP Mixes

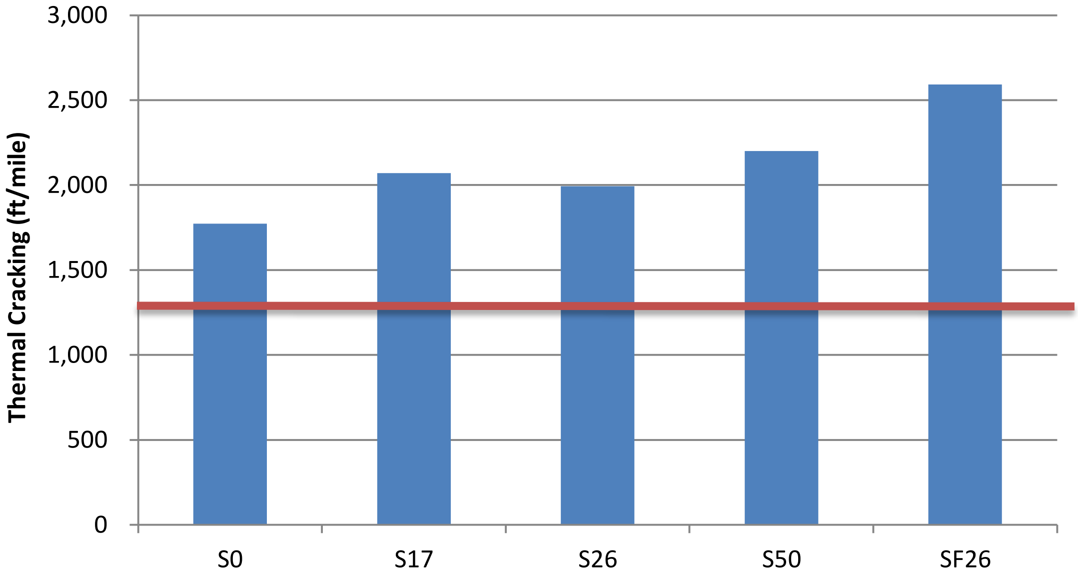


Figure 40. Thermal Cracking of South RAP Mixes

Chapter 6
Summary, Conclusions, and Recommendations

Summary

In order to verify ITD guidelines for using RAP in HMA in terms of the mixes' ability to provide the same performance as mixes without RAP, and to evaluate the effects of RAP on pavement performance, this study investigated a total of 10 mixes with different percentages of RAP, including 8 laboratory-produced mixes and 2 plant-produced mixes used in Idaho. The mix designs were in accordance with Superpave design method and current practice of virgin binder selection. RAP contents tested were 0, 17, 30, and 50 percent for the North mixes and 0, 17, 26, and 50 percent for the South mixes.

Following RAP characterization and mix design, the research team evaluated the laboratory performance of these mixes in terms of rutting resistance, fatigue cracking resistance, and low temperature thermal cracking resistance. The team conducted flow number and gyratory stability tests to determine the resistance to rutting and structural stability of asphalt mixes with different percentages of RAP**.** The team investigated the mixtures' resistance to fatigue cracking using IDT tests at 68°F. The team then used the fracture work density and vertical failure deformation values obtained from IDT tests to characterize the mixtures' resistance to bottom-up fatigue cracking and top-down fatigue cracking. Similarly, the team used the fracture work density values obtained from IDT tests at 14°F to evaluate the mixtures' resistance to low temperature thermal cracking.

The research team conducted mechanistic-empirical analysis using AASHTOWare Pavement ME Design software to evaluate the predicted field performance of HMA containing different percentages of RAP. The team compiled and measured material property, pavement structure, climate, and traffic data to derive the inputs for the mechanistic-empirical analysis. ITD designed and provided all the pavement structures. The research team compared all the predicted pavement distresses at 90 percent reliability over a design life of 20 years.

Conclusions

The laboratory experimental results indicate that resistance to rutting due to lateral shear failure, as indicated by the flow number, increased as RAP percentage increased. The mixtures' aggregate structure stability, as indicated by the gyratory stability test results, was comparable to or slightly better than that of the control mix. Overall, as expected, RAP mixes performed the same as or better than the control mixes in terms of rutting resistance. The results also indicate that at high RAP percentages, the binder grade adjustment does not offset the stiffening effects of RAP; this outcome is likely due to the incomplete blending between RAP binder and virgin binder.

In terms of fatigue cracking resistance, all of the North mixes performed comparably to each other for both bottom-up and top-down fatigue cracking resistance, even for the mixes with high percentages of

RAP, i.e., N30, N50, and NF30. However, the South mixes with high percentages of RAP, i.e., S26, S50, and SF26, exhibited less resistance to bottom-up fatigue cracking and top-down cracking than the control mix and the mix with a low percentage of RAP (S17). The resistance to low temperature thermal cracking was compromised for both the North and South RAP mixes; this outcome was likely due to the incomplete blending between RAP binder and virgin binder. In addition, the specification of the use of soft binder for high RAP mix may lead to the change of the use of polymer modifier binder to unmodified or less modified binder, which may compromise the fatigue performance, such as the case of South RAP mixes.

When PG of the virgin binder as per the blending chart was too low (e.g., PG 40-40), the use of virgin binder available in the market, which has a higher PG than that as per the blending chart for high (> 30 percent) RAP mixes, did not seem to compromise the performance of the mixes. Therefore, the use of such virgin binder should be encouraged, such as the case of the South RAP binder. In fact, the high temperature target PG is preferred to avoid the loss of use or reduced use of polymer in the virgin binder.

AASHTOWare Pavement ME Design predictions of pavement performance followed the trend of the laboratory properties of the mixes, because those same material properties are used in the performance models found in AASHTOWare Pavement ME Design. The thermal cracking of pavements containing high RAP percentages could be a concern and could compromise pavement performance.

Based on the project results, the performance of high RAP mixes in terms of fatigue cracking resistance and low temperature thermal cracking resistance may not be comparable to that of the control mix. In addition, the use of soft binder based on current ITD practice may not always improve a mixture's resistance to fatigue cracking and low temperature cracking. Factors other than RAP percentage may play a significant role in the performance of a pavement. The thoroughness of the blending between the soft virgin binder and RAP binder could affect the performance of RAP mixes. The use of a recycling agent, higher mixing temperature, or longer mixing time (e.g., slower drum rotational speed) during the production of high percentage RAP mixes could possibly improve the thoroughness of the blending process. However, it would be difficult for an agency to control the latter two parameters. The most effective method is to control the end product, namely the asphalt mixes.

Recommendations for Implementation

It is recommended that the high temperature PG of target binder is used regardless of RAP percentage to avoid loss of polymer modification of asphalt binder and ensure the rutting performance of RAP mix.

The research team recommends a performance-based mix design for mixes that contain high percentages of RAP. The team also recommends the addition of fracture criteria for fatigue cracking and thermal cracking for the mix design. The fracture criterion would be established by coring and testing samples of existing pavements with and without cracking. The research team further recommends that *AASHTO T283-14, Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture Induced Damage*, should replace the current moisture susceptibility test, which is based on unconfined compressive strength, during the mix design process.(2) *AASHTO T283-14* could help determine the moisture susceptibility as well as the fracture resistance of a given mix.

Alternatively, if it is difficult to include a cracking performance test in a mix design, the empirical model to determine the low temperature grade of virgin binder for RAP mix is recommended to use, after further validation, instead of the grade bumping and blending chart. The developed procedures for further validation are as follows:

1. Design a control mix without RAP to meet ITD specification with a binder of target PG.

2. Estimate fracture work density of control mix at low temperature ($FWD_{low\_control}$), based on Figure 41:

$$FWD_{low\_control}=9.437+0.179P_{RAP}-5.209AV+6.690VMA_{control}+1.475PG_{target\_low}-0.513PG_{target\_high}$$

where:

$FWD_{low\_control}$ = Fracture work density of control mix at low temperature, psi.
P_{RAP} = Percentage of RAP, percent; 0 percent in this case.
AV = Design air void, 4 percent in most cases.
$VMA_{control}$ = Void in mineral aggregate of control mix, percent.
PG_{target_low} = Low temperature grade of target binder.
PG_{target_high} = High temperature grade of target binder.

Figure 41. Prediction of Fracture Work Density of Control Mix at Low Temperature

3. Design RAP mix to meet ITD specification with a binder of PG_{virgin_high} and any low temperature PG, because the low temperature PG of binder does not significantly affect the volumetrics of a mix. The high temperature PG of target binder is recommended to be used for RAP mix.

4. Determine the low temperature PG of virgin binder for RAP mix using equation as Figure 42, based on RAP mix's design air void, VMA, P_{RAP}, $FWD_{low\_control}$, and PG_{virgin_high}.

$$PG_{virgin\_low}=(FWD_{low\_control}-9.437-0.179P_{RAP}+5.209AV-6.690VMA_{RAP}+0.513PG_{virgin\_high})/1.475$$

where:

$FWD_{low\_control}$ = Fracture work density of control mix at low temperature from Step 2, psi.
P_{RAP} = Percentage of RAP, percent.
AV = Design air void, 4 percent in most cases.
VMA_{RAP} = Void in mineral aggregate of RAP mix, percent.
PG_{virgin_low} = Low temperature grade of virgin binder.
PG_{virgin_high} = High temperature grade of virgin binder.

Figure 42. Virgin Binder Selection of Low Performance Grade for RAP Mixes

Further Studies

Based on the recommendations for implementation, the following studies are needed:

1. A cracking criterion of performance test for mix design is recommended to be developed.

2. RAP mix design procedure based on the empirical model developed in study should be validated with more RAP mixes, especially with plant mixes, as well as field performance.

3. This study focused on the effects of RAP in HMA. The South plant-produced mix was a WMA mix. However, because the research team reheated this foaming WMA mix in the laboratory before compaction, WMA mix was actually a HMA mix. The effects of RAP on WMA could be different from the effects on HMA, because the relatively lower mixing temperature used for WMA mixes could complicate certain factors, such as the thoroughness of the blending process. Therefore, the research team recommends further study of the effects of high RAP percentages on WMA mixes.

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Appendix A
Mix Design Results

Table 13. Optimum Asphalt Contents and Volumetric Properties of North Mixes

	N0	N17	N30	N50	NF30	SPECS.
PG of Virgin Binder	58-28	58-28	52-34	52-34	52-34	---
Optimum AC (%) (In Total)	4.9	4.5	4.8	4.7	4.8	---
Virgin Asphalt Added (%)	4.9	3.7	3.4	2.4	3.4	---
G_{mm}	2.505	2.517	2.505	2.505	2.491 (2.504)*	---
G_{mb}	2.403	2.415	2.404	2.406	2.392	---
Air Voids (%)	4.1	4.1	4.0	4.0	4.0	4.0
$\%G_{mm}@N_{des}$	95.9	96.0	96.0	96.0	96.0	96.0
$\%G_{mm}@N_{ini}$	85.8	85.6	85.8	86.1	-	$\leqslant$ 89.0
VMA (%)	14.3	13.2	13.7	13.3	14.0	13 min.
VFA (%)	72.0	69.0	71.0	71.0	71.0	65-75
Dust-to-Asphalt Ratio (DR)	1.3	1.5	1.4	1.4	1.4	0.8-1.6
$\%G_{mm}@N_{max}$	97.5	97.6	97.4	97.6	97.2	$\leqslant$ 98.0

* The value of 2.504 was tested in the laboratory for the G_{mm} of loose mix, and the difference is within d2s, as mentioned in AASHTO T209-12.(56)

Table 14. Optimum Asphalt Contents and Volumetric Properties of South Mixes

	S0	S17	S26	S50	SF26	SPECS.
PG of Virgin Binder	70-28	70-28	64-34	58-34	64-34	---
Optimum AC (%) (In Total)	5.0	5.2	4.8	4.8	5.2	---
Virgin Asphalt Added (%)	5.0	4.3	3.6	2.4	3.8	---
G_{mm}	2.413	2.432	2.421	2.434	2.418 (2.412)*	---
G_{mb}	2.317	2.336	2.325	2.336	2.322	---
Air Voids (%)	4.0	4.0	4.0	4.0	4.0	4.0
$\%G_{mm}@N_{des}$	96.0	96.0	96.0	96.0	96.0	96.0
$\%G_{mm}@N_{ini}$	89.2**	88.8	89.0	88.8	-	$\leqslant$ 89.0
VMA (%)	15.1	14.5	14.5	14.0	14.6	14 min.
VFA (%)	74.0	73.0	73.0	71.0	73.0	65-75
Dust-to-Asphalt Ratio (DR)	1.1	1.2	1.2	1.3**	1.2	0.6-1.2
$\%G_{mm}@N_{max}$	97.2	97.3	97.2	97.3	97.4	$\leqslant$ 98.0

* The value of 2.412 was tested in the laboratory for G_{mm} of loose mix, and the difference is within d2s, as mentioned in AASHTO T209-12;(56)

**Values are out of specification range.

Appendix B
Laboratory Performance Test Data

Table 15. Averaged Dynamic Modulus Test Results of North Mixes

	N0		N17		N30		N50		NF30	
Temp. (°F)	**Frequency (Hz)**	**Modulus (psi)**	**Frequency (Hz)**	**Modulus (psi)**	**Frequency (Hz)**	**Modulus (psi)**	**Frequency (Hz)**	**Modulus (psi)**	**Frequency (Hz)**	**Modulus (psi)**
40	25.0	1,436,091	25.0	1,549,945	25.0	1,602,232	25.0	1,794,189	25.0	1,782,296
40	10.0	1,218,027	10.0	1,325,717	10.0	1,388,881	10.0	1,606,510	10.0	1,560,896
40	5.0	1,062,691	5.0	1,155,515	5.0	1,229,630	5.0	1,466,984	5.0	1,390,912
40	1.0	740,272	1.0	805,394	1.0	893,722	1.0	1,145,435	1.0	1,005,474
40	0.5	620,544	0.5	682,475	0.5	758,547	0.5	1,013,233	0.5	856,883
40	0.1	382,754	0.1	426,411	0.1	502,701	0.1	733,601	0.1	552,304
70	25.0	457,376	25.0	513,433	25.0	578,991	25.0	809,020	25.0	660,719
70	10.0	340,041	10.0	380,651	10.0	445,701	10.0	649,044	10.0	509,372
70	5.0	265,927	5.0	298,560	5.0	360,854	5.0	545,632	5.0	402,480
70	1.0	135,240	1.0	151,927	1.0	203,198	1.0	335,690	1.0	207,549
70	0.5	99,380	0.5	112,114	0.5	155,916	0.5	271,366	0.5	154,175
70	0.1	44,991	0.1	51,365	0.1	76,464	0.1	150,912	0.1	70,539
100	25.0	155,198	25.0	118,605	25.0	148,954	25.0	246,347	25.0	219,696
100	10.0	98,981	10.0	72,700	10.0	97,755	10.0	175,496	10.0	145,603
100	5.0	67,950	5.0	49,835	5.0	69,647	5.0	133,087	5.0	101,338
100	1.0	36,796	1.0	19,790	1.0	29,254	1.0	63,113	1.0	42,402
100	0.5	27,441	0.5	13,423	0.5	20,102	0.5	45,498	0.5	29,044
100	0.1	12,437	0.1	6,258	0.1	8,963	0.1	20,704	0.1	13,148
130	25.0	74,992	25.0	41,807	25.0	46,238	25.0	71,953	25.0	75,405
130	10.0	48,957	10.0	20,472	10.0	24,932	10.0	42,764	10.0	43,584
130	5.0	18,209	5.0	12,785	5.0	16,259	5.0	28,899	5.0	28,181
130	1.0	12,546	1.0	5,424	1.0	6,773	1.0	12,045	1.0	11,951
130	0.5	6,810	0.5	4,163	0.5	8,021	0.5	8,622	0.5	8,782
130	0.1	4,061	0.1	2,531	0.1	4,888	0.1	4,453	0.1	5,214

Table 16. Flow Number Test Results of North RAP Mixes

Mixes	Mix Class	Binder Grade (PG)	AC (%)	Sample No.	Flow Number	Average Flow Number	Standard Deviation	COV (%)
N0	SP5	58-28	4.9	S1	185	209	27	12.9
	SP5	58-28	4.9	S2	239			
	SP5	58-28	4.9	S3	204			
N17	SP5	58-28	4.5	S1	175	192	18	9.4
	SP5	58-28	4.5	S2	211			
	SP5	58-28	4.5	S3	189			
N30	SP5	52-34	4.8	S1	256	263	31	11.8
	SP5	52-34	4.8	S2	297			
	SP5	52-34	4.8	S3	236			
N50	SP5	52-34	4.7	S1	465	518	64	12.4
	SP5	52-34	4.7	S2	589			
	SP5	52-34	4.7	S3	500			
NF30	SP5	52-34	4.8	S1	375	312	89	28.5
	SP5	52-34	4.8	S2	249			

Table 17. Multiple Comparisons of North Mixes Using ANOVA for Flow Number Test (p-value)

Mixes		Sig. for Flow Number Test
N0	N17	0.041[*]
	N30	0.021[*]
	N50	0.002[*]
	NF30	0.013[*]
N17	N0	0.041[*]
	N30	0.014[*]
	N50	0.003[*]
	NF30	0.009[*]
N30	N0	0.021[*]
	N17	0.014[*]
	N50	0.005[*]
	NF30	0.012[*]
N50	N0	0.002[*]
	N17	0.003[*]
	N30	0.005[*]
	NF30	0.009[*]
NF30	N0	0.013[*]
	N17	0.091[*]
	N30	0.012[*]
	N50	0.009[*]

[*] p-values are lower than 0.05.

Table 18. Gyratory Stability Test Results of North RAP Mixes

Mixes	Mix Class	Binder Grade (PG)	AC (%)	Sample No.	GS (kN·m) from GSC	Average GS (kN·m)	Standard Deviation (kN·m)	COV (%)
N0	SP5	58-28	4.9	S1	12.21	12.29	0.01	0.1
	SP5	58-28	4.9	S2	12.30			
	SP5	58-28	4.9	S3	12.28			
N17	SP5	58-28	4.5	S1	13.87	13.72	0.18	1.3
	SP5	58-28	4.5	S2	13.77			
	SP5	58-28	4.5	S3	13.52			
N30	SP5	52-34	4.8	S1	12.46	12.53	0.08	0.6
	SP5	52-34	4.8	S2	12.61			
	SP5	52-34	4.8	S3	12.53			
N50	SP5	52-34	4.7	S1	13.43	13.43	0.12	0.9
	SP5	52-34	4.7	S2	13.31			
	SP5	52-34	4.7	S3	13.55			
NF30	SP5	52-34	4.8	S1	12.93	12.72	0.30	2.4
	SP5	52-34	4.8	S2	12.51			

Table 19. Multiple Comparisons of North Mixes Using ANOVA for Gyratory Stability Test (p-value)

Mixes		Sig. for Gyratory Stability
N0	N17	0.003*
	N30	0.003*
	N50	0.002*
	NF30	0.160
N17	N0	0.003*
	N30	0.005*
	N50	0.106
	NF30	0.046*
N30	N0	0.003*
	N17	0.005*
	N50	0.006*
	NF30	0.317
N50	N0	0.002*
	N17	0.106
	N30	0.006*
	NF30	0.072
NF30	N0	0.160
	N17	0.046*
	N30	0.317
	N50	0.072

* p-values are lower than 0.05.

Table 20. Fracture Work Density of North Mixes from IDT Test at 68°F

Mixes		Fracture Work Density (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
N0	1	12.20	13.82	1.92	13.9
	2	13.32			
	3	15.94			
N17	1	13.46	12.76	0.96	7.6
	2	13.15			
	3	11.66			
N30	1	10.45	11.52	1.28	11.1
	2	12.94			
	3	11.17			
N50	1	12.72	12.91	1.16	9.0
	2	14.15			
	3	11.86			
NF30	1	12.34	13.23	0.79	5.9
	2	13.83			
	3	13.51			

Table 21. Vertical Failure Deformation of North Mixes from IDT Test at 68°F

Mixes		Vertical Failure Deformation (inch)	Average (inch)	Standard Deviation (inch)	COV (%)
N0	1	0.0576	0.0667	0.0111	16.7
	2	0.0633			
	3	0.0791			
N17	1	0.0715	0.0656	0.0069	10.5
	2	0.0671			
	3	0.0581			
N30	1	0.0695	0.0726	0.0079	10.9
	2	0.0816			
	3	0.0668			
N50	1	0.0588	0.0624	0.0121	19.4
	2	0.0759			
	3	0.0525			
NF30	1	0.0738	0.0604	0.0120	19.9
	2	0.0506			
	3	0.0568			

Table 22. IDT Strength of North Mixes at 68°F

Mixes		IDT Strength (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
N0	1	281	233	42	17.9
	2	207			
	3	212			
N17	1	302	298	12	4.2
	2	307			
	3	284			
N30	1	225	221	11	4.9
	2	208			
	3	229			
N50	1	311	296	31	10.4
	2	261			
	3	317			
NF30	1	315	334	45	13.4
	2	385			
	3	302			

Table 23. Multiple Comparisons of North Mixes Using ANOVA for Fracture Work Density and Vertical Failure Deformation from IDT Fatigue Tests (p-value)

Mixes		Sig. for Fracture Work Density	Sig. for Vertical Failure Deformation
N0	N17	0.842	1.000
	N30	0.255	0.948
	N50	0.902	0.984
	NF30	0.977	0.939
N17	N0	0.842	1.000
	N30	0.761	0.910
	N50	1.000	0.995
	NF30	0.990	0.969
N30	N0	0.255	0.948
	N17	0.761	0.910
	N50	0.681	0.739
	NF30	0.512	0.605
N50	N0	0.902	0.984
	N17	1.000	0.995
	N30	0.681	0.739
	NF30	0.998	0.999
NF30	N0	0.977	0.939
	N17	0.990	0.969
	N30	0.512	0.605
	N50	0.998	0.999

Table 24. Fracture Work Density of North Mixes from IDT Strength Test at 14°F

Mixes		Fracture Work Density (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
N0	1	15.75	13.37	2.15	16.0
	2	12.76			
	3	11.60			
N17	1	9.25	8.93	0.33	3.7
	2	8.94			
	3	8.59			
N30	1	10.62	11.45	1.15	10.1
	2	10.96			
	3	12.77			
N50	1	10.02	9.69	0.65	6.7
	2	10.11			
	3	8.94			
NF30	1	7.28	7.96	1.45	18.2
	2	9.62			
	3	6.97			

Table 25. Indirect Tensile Strength of North Mixes from IDT Strength Test at 14°F

Mixes		Indirect Tensile Strength (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
N0	1	525	472	51	10.8
	2	469			
	3	423			
N17	1	610	591	30	5.2
	2	606			
	3	556			
N30	1	486	475	13	2.7
	2	478			
	3	461			
N50	1	522	570	87	15.2
	2	670			
	3	517			
NF30	1	540	562	29	5.3
	2	595			
	3	550			

Table 26. Creep Compliance of North Mixes

Mixes		Average Creep Compliance (1/Pa)			m-value
	Temp (°F) Time (s)	-4	14	32	
N0	1	4.963E-11	5.478E-11	7.399E-11	0.2518
	2	5.287E-11	5.961E-11	8.518E-11	
	5	5.803E-11	6.510E-11	1.028E-10	
	10	6.266E-11	7.272E-11	1.218E-10	
	20	6.921E-11	8.131E-11	1.424E-10	
	50	7.931E-11	9.741E-11	1.900E-10	
	100	8.866E-11	1.124E-10	2.389E-10	
N17	1	2.609E-11	3.104E-11	3.786E-11	0.1525
	2	2.645E-11	3.392E-11	4.031E-11	
	5	2.745E-11	3.470E-11	4.671E-11	
	10	2.847E-11	3.793E-11	4.900E-11	
	20	2.970E-11	4.089E-11	5.525E-11	
	50	3.196E-11	4.050E-11	6.334E-11	
	100	3.331E-11	4.174E-11	7.957E-11	
N30	1	3.358E-11	4.311E-11	7.125E-11	0.1534
	2	3.463E-11	4.566E-11	7.622E-11	
	5	3.600E-11	4.918E-11	8.659E-11	
	10	3.845E-11	5.300E-11	9.619E-11	
	20	4.075E-11	5.575E-11	1.050E-10	
	50	4.454E-11	6.375E-11	1.237E-10	
	100	4.737E-11	7.259E-11	1.462E-10	
N50	1	2.668E-11	2.925E-11	4.240E-11	0.1601
	2	2.732E-11	3.074E-11	4.553E-11	
	5	2.854E-11	3.305E-11	5.227E-11	
	10	3.060E-11	3.470E-11	5.858E-11	
	20	3.130E-11	3.745E-11	6.469E-11	
	50	3.319E-11	4.152E-11	7.773E-11	
	100	3.516E-11	4.619E-11	9.122E-11	
NF30	1	3.267E-11	4.154E-11	5.643E-11	0.1199
	2	3.392E-11	4.193E-11	5.958E-11	
	5	3.431E-11	4.598E-11	6.622E-11	
	10	3.672E-11	4.734E-11	7.172E-11	
	20	3.794E-11	4.873E-11	7.778E-11	
	50	3.988E-11	5.264E-11	8.788E-11	
	100	4.304E-11	5.540E-11	9.799E-11	

Table 27. Multiple Comparisons of North Mixes Using ANOVA for Fracture Work Density from IDT Strength Tests (p-value)

Mixes		Sig. for Fracture Work Density
N0	N17	0.013[*]
	N30	0.425
	N50	0.039[*]
	NF30	0.003[*]
N17	N0	0.013[*]
	N30	0.203
	N50	0.948
	NF30	0.887
N30	N0	0.425
	N17	0.203
	N50	0.503
	NF30	0.052
N50	N0	0.039[*]
	N17	0.948
	N30	0.503
	NF30	0.516
NF30	N0	0.003[*]
	N17	0.887
	N30	0.052
	N50	0.516

[*] p-values are lower than 0.05.

Table 28. Averaged Dynamic Modulus Test Results of South Mixes

	S0		S17		S26		S50		SF26	
Temp. (°F)	Frequency (Hz)	Modulus (psi)	Frequency (Hz)	Modulus (psi)	Frequency (Hz)	Modulus (psi)	Frequency (Hz)	Modulus (psi)	Frequency (Hz)	Modulus (psi)
40	25.0	1,831,826	25.0	1,940,604	25.0	1,598,316	25.0	1,822,399	25.0	1,321,148
40	10.0	1,631,529	10.0	1,693,025	10.0	1,422,675	10.0	1,664,598	10.0	1,157,256
40	5.0	1,491,713	5.0	1,560,026	5.0	1,289,385	5.0	1,539,720	5.0	1,031,508
40	1.0	1,163,347	1.0	1,241,958	1.0	992,203	1.0	1,242,538	1.0	763,043
40	0.5	1,033,249	0.5	1,114,615	0.5	876,173	0.5	1,117,806	0.5	659,051
40	0.1	742,593	0.1	824,539	0.1	630,334	0.1	846,730	0.1	444,250
70	25.0	805,684	25.0	883,860	25.0	688,059	25.0	887,631	25.0	492,983
70	10.0	647,158	10.0	711,410	10.0	547,517	10.0	727,509	10.0	378,113
70	5.0	531,708	5.0	594,655	5.0	452,373	5.0	617,425	5.0	303,274
70	1.0	314,732	1.0	369,556	1.0	276,152	1.0	399,289	1.0	168,389
70	0.5	248,595	0.5	300,373	0.5	224,518	0.5	331,411	0.5	127,488
70	0.1	128,373	0.1	168,244	0.1	126,038	0.1	196,091	0.1	62,917
100	25.0	234,091	25.0	271,945	25.0	208,419	25.0	291,671	25.0	179,122
100	10.0	163,167	10.0	194,205	10.0	148,519	10.0	214,511	10.0	121,469
100	5.0	120,512	5.0	147,503	5.0	111,679	5.0	166,068	5.0	87,574
100	1.0	56,188	1.0	72,142	1.0	54,824	1.0	84,455	1.0	39,276
100	0.5	40,973	0.5	52,547	0.5	41,046	0.5	63,265	0.5	28,079
100	0.1	19,856	0.1	25,643	0.1	20,450	0.1	30,371	0.1	13,561
130	25.0	64,991	25.0	81,265	25.0	95,130	25.0	90,881	25.0	125,878
130	10.0	41,452	10.0	53,113	10.0	65,673	10.0	60,075	10.0	81,932
130	5.0	28,848	5.0	37,623	5.0	46,876	5.0	42,148	5.0	54,882
130	1.0	13,648	1.0	17,695	1.0	21,727	1.0	19,159	1.0	23,148
130	0.5	10,486	0.5	13,489	0.5	15,983	0.5	13,967	0.5	16,607
130	0.1	6,150	0.1	7,484	0.1	8,456	0.1	7,484	0.1	8,818

Table 29. Flow Number Test Results of South RAP Mixes

Mixes	Mix Class	Binder Grade (PG)	AC (%)	Sample No.	Flow Number	Average Flow Number	Standard Deviation	COV (%)
S0	SP4	70-28	5.0	S1	910	910	62	6.8
	SP4	70-28	5.0	S2	972			
	SP4	70-28	5.0	S3	848			
S17	SP4	70-28	5.2	S1	820	852	97	11.4
	SP4	70-28	5.2	S2	961			
	SP4	70-28	5.2	S3	774			
S26	SP4	64-34	4.8	S1	1171	1,117	57	5.1
	SP4	64-34	4.8	S2	1057			
	SP4	64-34	4.8	S3	1123			
S50	SP4	58-34	4.8	S1	1237	1,258	75	6.0
	SP4	58-34	4.8	S2	1341			
	SP4	58-34	4.8	S3	1195			
SF26	SP4	64-34	5.2	S1	1293	1,357	91	6.7
	SP4	64-34	5.2	S2	1421			

Table 30. Multiple Comparisons of South Mixes Using ANOVA for Flow Number Test (p-value)

Mixes		Sig. for Flow Number test
S0	S17	0.068
	S26	0.039[*]
	S50	0.001[*]
	SF26	0.025[*]
S17	S0	0.068
	S26	0.044[*]
	S50	0.001[*]
	SF26	0.004[*]
S26	S0	0.039[*]
	S17	0.044[*]
	S50	0.094
	SF26	0.147
S50	S0	0.001[*]
	S17	0.001[*]
	S26	0.094
	SF26	0.056
SF26	S0	0.025[*]
	S17	0.004[*]
	S26	0.147
	S50	0.056

[*] p-values are lower than 0.05.

Table 31. Gyratory Stability Test Results of South RAP Mixes

Mixes	Sample No.	Binder Grade (PG)	AC (%)	Sample No.	GS (kN·m) from GSC	Average GS (kN·m)	Standard Deviation (kN·m)	COV (%)
S0	SP4	70-28	5.0	S1	12.58	12.98	0.37	2.9
	SP4	70-28	5.0	S2	13.04			
	SP4	70-28	5.0	S3	13.32			
S17	SP4	70-28	5.2	S1	13.23	13.26	0.09	0.7
	SP4	70-28	5.2	S2	13.36			
	SP4	70-28	5.2	S3	13.18			
S26	SP4	64-34	4.8	S1	13.04	13.12	0.09	0.7
	SP4	64-34	4.8	S2	13.21			
	SP4	64-34	4.8	S3	13.10			
S50	SP4	58-34	4.8	S1	13.38	13.38	0.15	1.1
	SP4	58-34	4.8	S2	13.52			
	SP4	58-34	4.8	S3	13.23			
SF26	SP4	64-34	5.2	S1	12.33	12.24	0.13	1.1
	SP4	64-34	5.2	S2	12.14			

Table 32. Multiple Comparisons of South Mixes Using ANOVA for Gyratory Stability Test (p-value)

Mixes		Sig. for Gyratory Stability Test
S0	S17	0.175
	S26	0.280
	S50	0.133
	SF26	0.164
S17	S0	0.175
	S26	0.024*
	S50	0.038*
	SF26	0.048*
S26	S0	0.280
	S17	0.024*
	S50	0.029*
	SF26	0.064
S50	S0	0.133
	S17	0.038*
	S26	0.029*
	SF26	0.043*
SF26	S0	0.164
	S17	0.048*
	S26	0.064
	S50	0.043*

* p-values are lower than 0.05.

Table 33. Fracture Work Density of South Mixes from IDT Test at 68°F

Mixes		Fracture Work Density (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
S0	1	12.53	12.77	0.59	4.6
	2	12.33			
	3	13.44			
S17	1	10.99	12.17	1.03	8.4
	2	12.84			
	3	12.69			
S26	1	9.19	8.89	0.68	7.7
	2	8.10			
	3	9.37			
S50	1	11.18	10.03	1.02	10.2
	2	9.22			
	3	9.69			
SF26	1	10.88	9.88	0.98	10.0
	2	8.91			
	3	9.84			

Table 34. Vertical Failure Deformation of South Mixes from IDT Test at 68°F

Mixes		Vertical Failure Deformation (inch)	Average (inch)	Standard Deviation (inch)	COV (%)
S0	1	0.0569	0.0562	0.0008	1.4
	2	0.0563			
	3	0.0554			
S17	1	0.0601	0.0620	0.0025	4.0
	2	0.0648			
	3	0.0612			
S26	1	0.0494	0.0465	0.0033	7.1
	2	0.0474			
	3	0.0429			
S50	1	0.0472	0.0487	0.0049	10.1
	2	0.0542			
	3	0.0448			
SF26	1	0.0474	0.0521	0.0048	9.3
	2	0.0519			
	3	0.0571			

Table 35. IDT Strength of South Mixes at 68°F

Mixes		IDT Strength (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
S0	1	574	619	39	6.3
	2	645			
	3	638			
S17	1	602	634	36	5.7
	2	673			
	3	627			
S26	1	434	442	14	3.1
	2	433			
	3	458			
S50	1	522	532	12	2.3
	2	529			
	3	545			
SF26	1	463	467	5	1.0
	2	472			
	3	467			

Table 36. Multiple Comparisons of South Mixes Using ANOVA for Fracture Work Density and Vertical Failure Deformation from IDT Fatigue Tests (p-value)

Mixes		Sig. for Fracture Work Density	Sig. for Vertical Failure Deformation
S0	S17	0.917	0.340
	S26	0.002*	0.052
	S50	0.023*	0.158
	SF26	0.016*	0.652
S17	S0	0.917	0.340
	S26	0.007*	0.003*
	S50	0.082	0.008*
	SF26	0.059	0.045*
S26	S0	0.002*	0.052
	S17	0.007*	0.003*
	S50	0.536	0.943
	SF26	0.656	0.381
S50	S0	0.023*	0.158
	S17	0.082	0.008*
	S26	0.536	0.943
	SF26	0.999	0.776
SF26	S0	0.016*	0.652
	S17	0.059	0.045*
	S26	0.656	0.381
	S50	0.999	0.776

* p-values are lower than 0.05.

Table 37. Fracture Work Density of South Mixes from IDT Strength Test at 14°F

Mixes		Fracture Work Density (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
S0	1	11.02	11.83	1.39	11.7
	2	13.43			
	3	11.05			
S17	1	12.89	12.21	1.58	13.0
	2	13.34			
	3	10.40			
S26	1	7.97	6.92	1.05	15.2
	2	6.92			
	3	5.86			
S50	1	10.48	11.56	1.00	8.6
	2	11.76			
	3	12.44			
SF26	1	9.20	9.36	0.23	2.5
	2	9.26			
	3	9.63			

Table 38. Indirect Tensile Strength of South Mixes from IDT Strength Test at 14°F

Mixes		Indirect Tensile Strength (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
S0	1	764	746	87	11.7
	2	822			
	3	651			
S17	1	810	785	40	5.1
	2	806			
	3	739			
S26	1	456	479	29	6.1
	2	512			
	3	469			
S50	1	700	720	55	7.6
	2	678			
	3	782			
SF26	1	599	640	35	5.5
	2	660			
	3	660			

Table 39. Creep Compliance of South Mixes

Mixes		Average Creep Compliance (1/Pa)			m-value
	Temp (°F) Time (s)	-4	14	32	
S0	1	2.785E-11	3.539E-11	4.507E-11	0.0591
	2	2.860E-11	3.641E-11	4.671E-11	
	5	2.906E-11	3.748E-11	4.853E-11	
	10	2.946E-11	3.897E-11	5.166E-11	
	20	3.100E-11	3.983E-11	5.355E-11	
	50	3.174E-11	4.287E-11	5.707E-11	
	100	3.343E-11	4.446E-11	5.845E-11	
S17	1	2.805E-11	3.225E-11	3.821E-11	0.0864
	2	2.841E-11	3.285E-11	3.947E-11	
	5	3.008E-11	3.477E-11	4.240E-11	
	10	3.027E-11	3.634E-11	4.561E-11	
	20	3.131E-11	3.746E-11	4.839E-11	
	50	3.266E-11	3.936E-11	5.274E-11	
	100	3.425E-11	4.180E-11	5.620E-11	
S26	1	3.687E-11	4.456E-11	5.617E-11	0.0941
	2	3.796E-11	4.593E-11	5.799E-11	
	5	3.938E-11	4.846E-11	6.326E-11	
	10	4.118E-11	5.042E-11	6.801E-11	
	20	4.238E-11	5.290E-11	7.329E-11	
	50	4.401E-11	5.690E-11	7.923E-11	
	100	4.663E-11	6.006E-11	8.567E-11	
S50	1	3.305E-11	4.160E-11	4.705E-11	0.0623
	2	3.351E-11	4.225E-11	4.833E-11	
	5	3.412E-11	4.492E-11	5.013E-11	
	10	3.516E-11	4.567E-11	5.194E-11	
	20	3.653E-11	4.779E-11	5.583E-11	
	50	3.759E-11	4.793E-11	5.897E-11	
	100	3.882E-11	4.718E-11	6.236E-11	
SF26	1	3.864E-11	4.305E-11	5.114E-11	0.0767
	2	3.983E-11	4.282E-11	5.216E-11	
	5	4.091E-11	4.543E-11	5.610E-11	
	10	4.238E-11	4.790E-11	6.007E-11	
	20	4.345E-11	4.859E-11	6.265E-11	
	50	4.611E-11	4.973E-11	6.792E-11	
	100	4.908E-11	5.068E-11	7.188E-11	

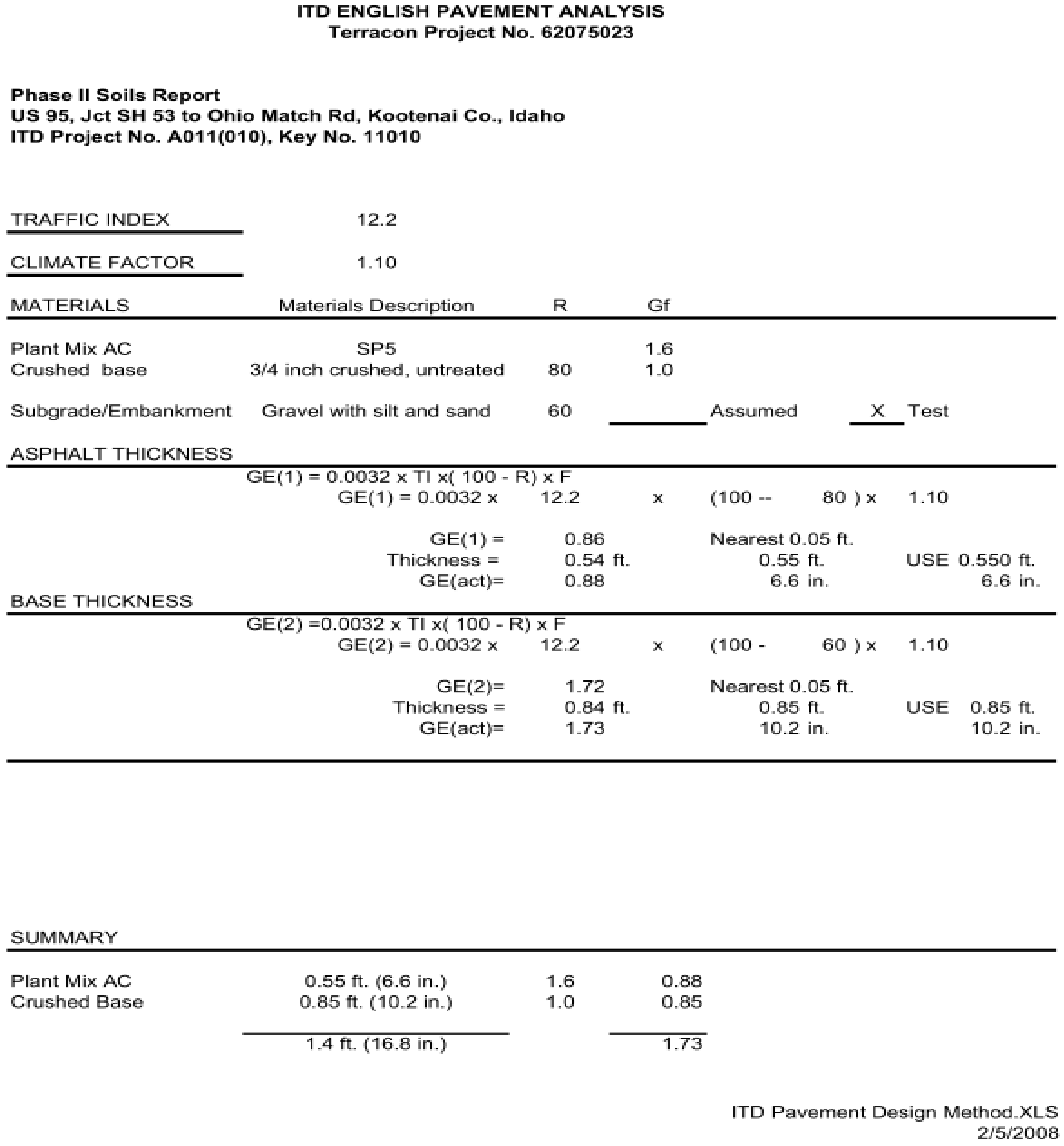
Table 40. Multiple Comparisons of South Mixes Using ANOVA for Fracture Work Density from IDT Strength Tests (p-value)

Mixes		Sig. for Fracture Work Density
S0	S17	0.994
	S26	0.003[*]
	S50	0.998
	SF26	0.136
S17	S0	0.994
	S26	0.002[*]
	S50	0.953
	SF26	0.074
S26	S0	0.003[*]
	S17	0.002[*]
	S50	0.004[*]
	SF26	0.141
S50	S0	0.998
	S17	0.953
	S26	0.004[*]
	SF26	0.208
SF26	S0	0.136
	S17	0.074
	S26	0.141
	S50	0.208

[*] p-values are lower than 0.05.

Appendix C
AASHTOWare Pavement ME Design Inputs

This Appendix presents data that were used for AASHTOWare Pavement ME Design. Some data, e.g. asphalt layer properties, were measured directly in the lab. However, other data, such as Traffic, Pavement structure, Layers properties, and project location were provided by the Idaho Transportation Department.



ITD ENGLISH PAVEMENT ANALYSIS
Terracon Project No. 62075023

Phase II Soils Report
US 95, Jct SH 53 to Ohio Match Rd, Kootenai Co., Idaho
ITD Project No. A011(010), Key No. 11010

TRAFFIC INDEX	12.2
CLIMATE FACTOR	1.10

MATERIALS	Materials Description	R	Gf		
Plant Mix AC	SP5		1.6		
Crushed base	3/4 inch crushed, untreated	80	1.0		
Subgrade/Embankment	Gravel with silt and sand	60	______ Assumed	X Test	

ASPHALT THICKNESS

GE(1) = 0.0032 x TI x(100 - R) x F
GE(1) = 0.0032 x 12.2 x (100 -- 80) x 1.10

GE(1) =	0.86	Nearest 0.05 ft.	
Thickness =	0.54 ft.	0.55 ft.	USE 0.550 ft.
GE(act)=	0.88	6.6 in.	6.6 in.

BASE THICKNESS

GE(2) =0.0032 x TI x(100 - R) x F
GE(2) = 0.0032 x 12.2 x (100 - 60) x 1.10

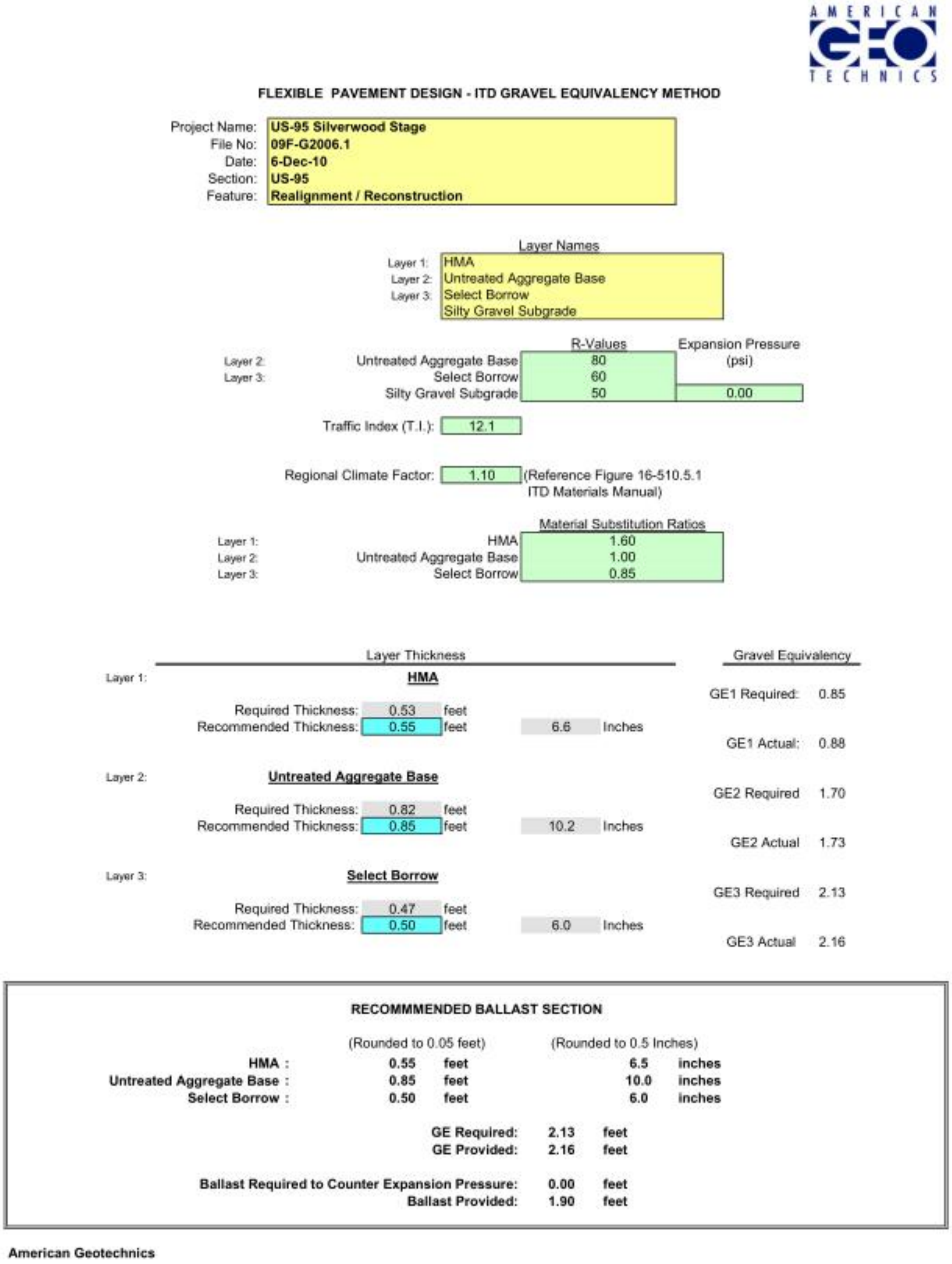
GE(2)=	1.72	Nearest 0.05 ft.	
Thickness =	0.84 ft.	0.85 ft.	USE 0.85 ft.
GE(act)=	1.73	10.2 in.	10.2 in.

SUMMARY

Plant Mix AC	0.55 ft. (6.6 in.)	1.6	0.88
Crushed Base	0.85 ft. (10.2 in.)	1.0	0.85
	1.4 ft. (16.8 in.)		1.73

ITD Pavement Design Method.XLS
2/5/2008

Figure 43. Pavement Structure Design of the North Project



FLEXIBLE PAVEMENT DESIGN - ITD GRAVEL EQUIVALENCY METHOD

Project Name: **US-95 Silverwood Stage**
File No: **09F-G2006.1**
Date: **6-Dec-10**
Section: **US-95**
Feature: **Realignment / Reconstruction**

Layer Names
Layer 1: HMA
Layer 2: Untreated Aggregate Base
Layer 3: Select Borrow
Silty Gravel Subgrade

		R-Values	Expansion Pressure (psi)
Layer 2:	Untreated Aggregate Base	80	
Layer 3:	Select Borrow	60	
	Silty Gravel Subgrade	50	0.00

Traffic Index (T.I.): 12.1

Regional Climate Factor: 1.10 (Reference Figure 16-510.5.1 ITD Materials Manual)

		Material Substitution Ratios
Layer 1:	HMA	1.60
Layer 2:	Untreated Aggregate Base	1.00
Layer 3:	Select Borrow	0.85

	Layer Thickness					Gravel Equivalency	
Layer 1:	**HMA**					GE1 Required:	0.85
	Required Thickness:	0.53	feet				
	Recommended Thickness:	0.55	feet	6.6	Inches		
						GE1 Actual:	0.88
Layer 2:	**Untreated Aggregate Base**					GE2 Required	1.70
	Required Thickness:	0.82	feet				
	Recommended Thickness:	0.85	feet	10.2	Inches		
						GE2 Actual	1.73
Layer 3:	**Select Borrow**					GE3 Required	2.13
	Required Thickness:	0.47	feet				
	Recommended Thickness:	0.50	feet	6.0	Inches		
						GE3 Actual	2.16

RECOMMMENDED BALLAST SECTION

	(Rounded to 0.05 feet)		(Rounded to 0.5 Inches)	
HMA :	**0.55**	**feet**	**6.5**	**inches**
Untreated Aggregate Base :	**0.85**	**feet**	**10.0**	**inches**
Select Borrow :	**0.50**	**feet**	**6.0**	**inches**

GE Required: **2.13** **feet**
GE Provided: **2.16** **feet**

Ballast Required to Counter Expansion Pressure: **0.00** **feet**
Ballast Provided: **1.90** **feet**

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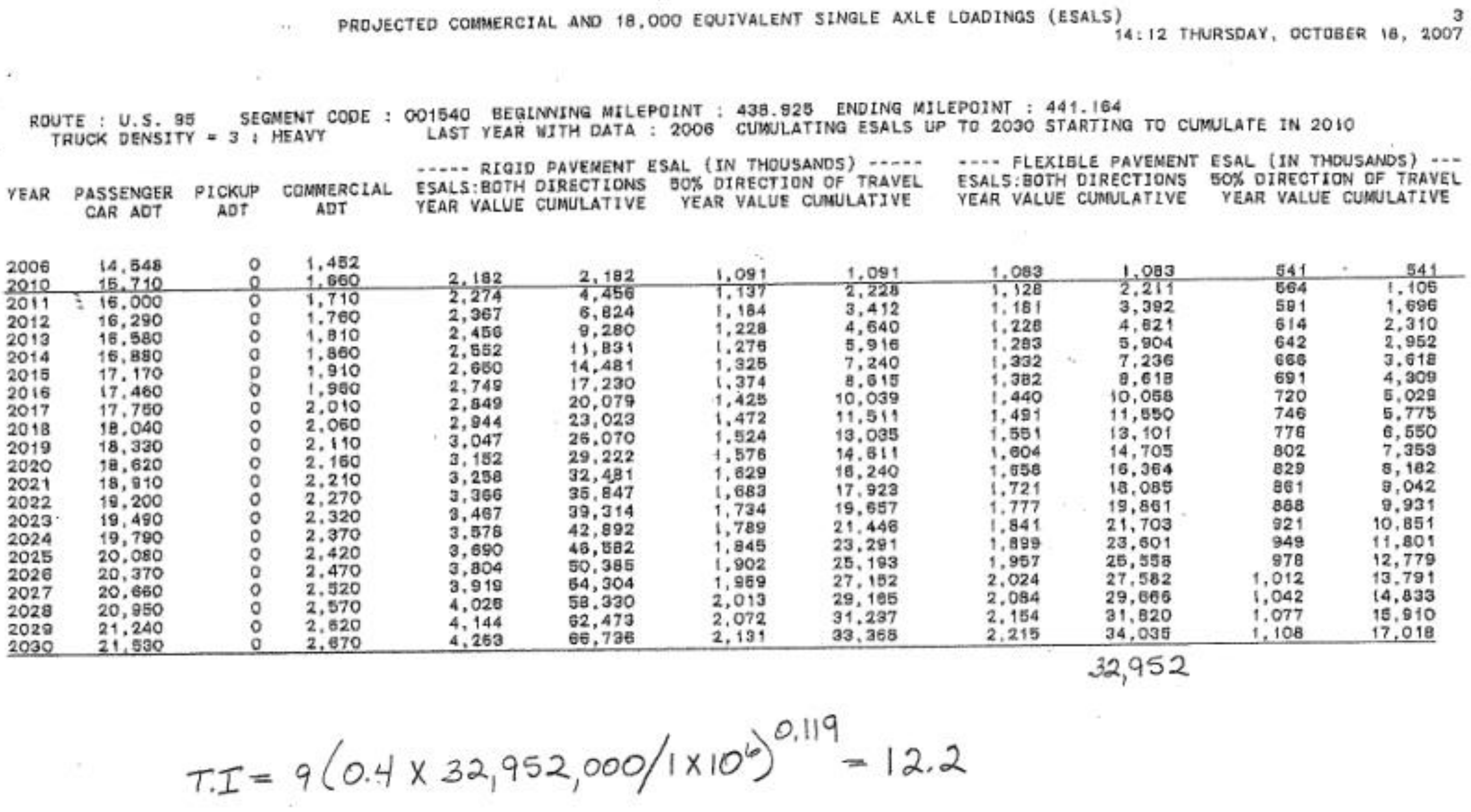
Figure 44. Pavement Structure Design of the North Project



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        PROJECTED COMMERCIAL AND 18,000 EQUIVALENT SINGLE AXLE LOADINGS (ESALS)                                3
                                                                                   14:12 THURSDAY, OCTOBER 18, 2007

 ROUTE : U.S. 95     SEGMENT CODE : 001540  BEGINNING MILEPOINT : 438.925  ENDING MILEPOINT : 441.164
   TRUCK DENSITY = 3 : HEAVY          LAST YEAR WITH DATA : 2006  CUMULATING ESALS UP TO 2030 STARTING TO CUMULATE IN 2010

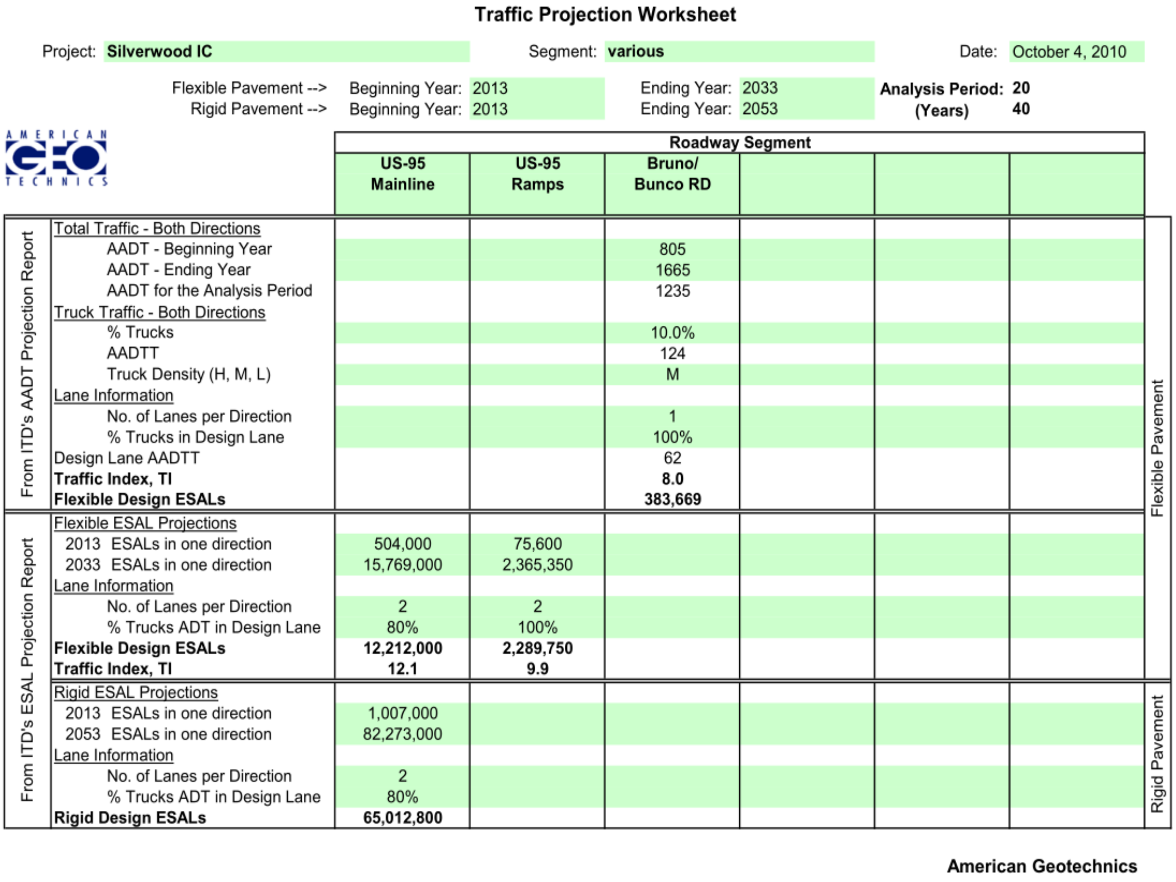
                                         ----- RIGID PAVEMENT ESAL (IN THOUSANDS) -----   ---- FLEXIBLE PAVEMENT ESAL (IN THOUSANDS) ---
 YEAR  PASSENGER  PICKUP  COMMERCIAL   ESALS:BOTH DIRECTIONS  50% DIRECTION OF TRAVEL    ESALS:BOTH DIRECTIONS  50% DIRECTION OF TRAVEL
        CAR ADT    ADT       ADT       YEAR VALUE CUMULATIVE   YEAR VALUE CUMULATIVE     YEAR VALUE CUMULATIVE   YEAR VALUE CUMULATIVE

 2006   14,548      0      1,452
 2010   15,710      0      1,660        2,182       2,182      1,091       1,091         1,083      1,083         541        541
 2011   16,000      0      1,710        2,274       4,456      1,137       2,228         1,128      2,211         564      1,105
 2012   16,290      0      1,760        2,367       6,824      1,184       3,412         1,181      3,392         591      1,696
 2013   16,580      0      1,810        2,456       9,280      1,228       4,640         1,228      4,821         614      2,310
 2014   16,880      0      1,860        2,552      11,831      1,276       5,916         1,283      5,904         642      2,952
 2015   17,170      0      1,910        2,650      14,481      1,325       7,240         1,332      7,236         666      3,618
 2016   17,460      0      1,960        2,749      17,230      1,374       8,615         1,382      8,618         691      4,309
 2017   17,750      0      2,010        2,849      20,079      1,425      10,039         1,440     10,058         720      5,029
 2018   18,040      0      2,060        2,944      23,023      1,472      11,511         1,491     11,550         746      5,775
 2019   18,330      0      2,110        3,047      26,070      1,524      13,035         1,551     13,101         776      6,550
 2020   18,620      0      2,160        3,152      29,222      1,576      14,611         1,604     14,705         802      7,353
 2021   18,910      0      2,210        3,258      32,481      1,629      16,240         1,658     16,364         829      8,182
 2022   19,200      0      2,270        3,366      35,847      1,683      17,923         1,721     18,085         861      9,042
 2023   19,490      0      2,320        3,467      39,314      1,734      19,657         1,777     19,861         888      9,931
 2024   19,790      0      2,370        3,578      42,892      1,789      21,446         1,841     21,703         921     10,851
 2025   20,080      0      2,420        3,690      46,582      1,845      23,291         1,899     23,601         949     11,801
 2026   20,370      0      2,470        3,804      50,385      1,902      25,193         1,957     25,558         978     12,779
 2027   20,660      0      2,520        3,919      54,304      1,959      27,152         2,024     27,582       1,012     13,791
 2028   20,950      0      2,570        4,028      58,330      2,013      29,165         2,084     29,666       1,042     14,833
 2029   21,240      0      2,620        4,144      62,473      2,072      31,237         2,154     31,820       1,077     15,910
 2030   21,530      0      2,670        4,263      66,736      2,131      33,368         2,215     34,035       1,108     17,018
```

32,952

$$T.I = 9\left(0.4 \times 32{,}952{,}000/1 \times 10^{6}\right)^{0.119} = 12.2$$

Figure 45. Projected ESAL Design of the North Project



Traffic Projection Worksheet

Project: **Silverwood IC** Segment: **various** Date: October 4, 2010

Flexible Pavement --> Beginning Year: 2013 Ending Year: 2033 **Analysis Period: 20**
Rigid Pavement --> Beginning Year: 2013 Ending Year: 2053 **(Years) 40**

		Roadway Segment						
		US-95 Mainline	**US-95 Ramps**	**Bruno/ Bunco RD**				
From ITD's AADT Projection Report	Total Traffic - Both Directions							Flexible Pavement
	AADT - Beginning Year			805				
	AADT - Ending Year			1665				
	AADT for the Analysis Period			1235				
	Truck Traffic - Both Directions							
	% Trucks			10.0%				
	AADTT			124				
	Truck Density (H, M, L)			M				
	Lane Information							
	No. of Lanes per Direction			1				
	% Trucks in Design Lane			100%				
	Design Lane AADTT			62				
	Traffic Index, TI			**8.0**				
	Flexible Design ESALs			**383,669**				
From ITD's ESAL Projection Report	Flexible ESAL Projections							
	2013 ESALs in one direction	504,000	75,600					
	2033 ESALs in one direction	15,769,000	2,365,350					
	Lane Information							
	No. of Lanes per Direction	2	2					
	% Trucks ADT in Design Lane	80%	100%					
	Flexible Design ESALs	**12,212,000**	**2,289,750**					
	Traffic Index, TI	**12.1**	**9.9**					
	Rigid ESAL Projections							Rigid Pavement
	2013 ESALs in one direction	1,007,000						
	2053 ESALs in one direction	82,273,000						
	Lane Information							
	No. of Lanes per Direction	2						
	% Trucks ADT in Design Lane	80%						
	Rigid Design ESALs	**65,012,800**						

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Figure 46. Projected ESAL Design of the North Project

Table 41. Traffic Input Data for North Mixes

Initial Two-Way AADTT	963
Number of Lanes in Design Direction	2
Percentage of Trucks in Design Direction (%)	51
Percentage of Trucks in Design Lane (%)	95

Table 42. Monthly Adjustment Factors (MAF) for North Mixes

	Vehicle Class									
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
January	0.627	0.926	1.304	0.138	0.506	0.923	0.861	0.000	3.000	0.686
February	0.745	0.870	0.900	0.113	0.482	1.060	1.207	0.000	3.000	1.371
March	0.667	0.852	0.569	0.283	0.699	0.960	1.018	0.000	3.000	1.371
April	0.980	0.778	0.477	2.965	0.940	0.973	0.966	4.000	0.000	1.200
May	1.137	0.783	0.523	2.086	0.867	0.848	0.630	0.000	0.000	0.686
June	1.255	1.103	1.184	1.363	1.253	1.098	0.903	0.000	0.000	0.857
July	1.647	1.458	1.598	1.275	1.470	1.010	1.081	0.000	0.000	0.857
August	1.647	1.476	1.607	1.338	1.759	1.148	1.228	4.000	0.000	0.857
September	1.804	1.226	1.845	2.268	1.639	1.198	1.291	4.000	3.000	1.371
October	0.784	0.989	0.927	0.088	1.181	1.173	1.186	0.000	0.000	1.371
November	0.431	0.910	0.597	0.050	0.771	0.998	0.997	0.000	0.000	0.686
December	0.275	0.629	0.468	0.031	0.434	0.611	0.630	0.000	0.000	0.686

Table 43. Vehicle Class Distribution for North Mixes

	Vehicle Class									
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
AADTT Distribution by Vehicle Class (%)	2.50	48.01	11.18	14.05	4.19	8.84	10.52	0.02	0.04	0.65

Table 44. Number of Axles per Truck Class for North Mixes

Vehicle Class	Axle Type			
	Single	**Tandem**	**Tridem**	**Quad**
4	1.59	0.34	0.00	0.00
5	2.00	0.00	0.00	0.00
6	1.00	1.00	0.00	0.00
7	1.00	0.22	0.83	0.10
8	2.52	0.60	0.00	0.00
9	1.25	1.87	0.00	0.00
10	1.03	0.85	0.95	0.26
11	4.21	0.29	0.01	0.00
12	3.24	1.16	0.07	0.01
13	3.32	1.79	0.14	0.02

Table 45. Traffic Input Data for South Mixes

Initial Two-Way AADTT	403
Number of Lanes in Design Direction	1
Percentage of Trucks in Design Direction (%)	57
Percentage of Trucks in Design Lane (%)	100

Table 46. Monthly Adjustment Factors (MAF) for South Mixes

	Vehicle Class									
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
January	0.667	0.714	1.261	2.400	0.441	0.890	0.826	0.462	3.000	0.932
February	0.933	0.749	0.555	1.200	0.514	0.965	0.826	0.923	0.000	0.932
March	0.800	0.807	0.303	0.300	0.686	0.999	0.860	0.923	0.000	1.049
April	0.933	0.929	0.353	0.300	0.980	1.024	0.959	0.923	0.000	0.932
May	1.200	0.981	0.807	0.600	1.151	1.091	1.058	1.385	0.000	1.049
June	0.933	1.196	1.160	2.100	1.396	1.141	1.124	1.385	3.000	1.049
July	1.200	1.358	2.218	1.800	1.543	0.873	0.926	0.923	3.000	0.816
August	1.200	1.219	2.017	1.500	1.249	0.906	1.058	0.923	0.000	0.816
September	1.467	1.120	1.210	0.900	1.200	1.057	1.388	1.385	0.000	0.932
October	1.333	1.179	0.857	0.600	1.469	1.150	1.157	1.385	3.000	1.282
November	0.800	0.999	0.706	0.300	0.955	1.049	1.058	0.923	0.000	1.165
December	0.533	0.749	0.555	0.000	0.416	0.856	0.760	0.462	0.000	1.049

Table 47. Vehicle Class Distribution for South Mixes

	Vehicle Class									
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
AADTT Distribution by Vehicle Class (%)	1.84	42.40	4.74	0.82	9.71	30.16	7.54	0.53	0.08	2.19

Table 48. Number of Axles per Truck Class for South Mixes

Vehicle Class	Axle Type			
	Single	Tandem	Tridem	Quad
4	1.59	0.34	0.00	0.00
5	2.00	0.00	0.00	0.00
6	1.00	1.00	0.00	0.00
7	1.00	0.22	0.83	0.10
8	2.52	0.60	0.00	0.00
9	1.25	1.87	0.00	0.00
10	1.03	0.85	0.95	0.26
11	4.21	0.29	0.01	0.00
12	3.24	1.16	0.07	0.01
13	3.32	1.79	0.14	0.02

Table 49. Complex Shear Modulus and Phase Angle of PG 58-28 Binder Used for North Mix

PG 58-28		
Temp. (°F)	**G* (Pa)**	**Delta**
41	13,051,770	45.08
55	4,224,799	53.24
70	1,087,786	61.18
85	265,478	67.70
100	68,041	73.19
115	19,596	78.23
130	6,450	82.71

Table 50. Complex Shear Modulus and Phase Angle of PG 52-34 Binder Used for North Mix

PG 52-34		
Temp. (°F)	**G* (Pa)**	**Delta**
41	7,271,604	48.67
55	2,509,810	55.83
70	633,783	63.41
85	140,605	70.13
100	32,048	75.98
115	8,680	81.79
130	2,663	87.18

Table 51. Complex Shear Modulus and Phase Angle of the North RAP Binder

North RAP PG 75.8-23.6		
Temp. (°F)	**G* (Pa)**	**Delta**
41	46,017,200	30.38
55	22,414,640	37.03
70	7,568,248	46.11
85	2,074,640	55.35
100	505,653	63.53
115	121,818	70.27
130	29,390	76.05

Table 52. Complex Shear Modulus and Phase Angle of PG 70-28 Binder Used for South Mix

PG 70-28		
Temp. (°F)	**G* (Pa)**	**Delta**
41	20,448,670	43.88
55	6,966,370	51.94
70	1,951,845	58.88
85	503,406	63.46
100	138,183	65.83
115	43,112	67.08
130	15,268	68.38

Table 53. Complex Shear Modulus and Phase Angle of PG 64-34 Binder Used for South Mix

PG 64-34		
Temp. (°F)	**G* (Pa)**	**Delta**
41	6,144,631	46.92
55	2,190,711	52.60
70	655,763	57.60
85	188,974	61.00
100	59,555	63.08
115	21,736	64.85
130	8,755	67.52

Table 54. Complex Shear Modulus and Phase Angle of PG 58-34 Binder Used for South Mix

PG 58-34		
Temp. (°F)	**G* (Pa)**	**Delta**
41	6,013,541	48.06
55	2,081,305	53.71
70	616,133	58.31
85	178,812	61.20
100	56,935	62.75
115	20,088	63.99
130	8,073	66.59

Table 55. Complex Shear Modulus and Phase Angle of the South RAP Binder

South RAP PG 85.2-16.8		
Temp. (°F)	**G* (Pa)**	**Delta**
41	72,593,120	24.95
55	36,033,970	32.17
70	14,177,180	40.69
85	4,497,793	49.86
100	1,254,442	58.35
115	336,904	65.38
130	92,641	71.16

Table 56. Complex Shear Modulus and Phase Angle of the North 0 Percent RAP Binder

N0 RAP		
Temp. (°F)	**G* (Pa)**	**Delta**
41	13,051,770	45.08
55	4,224,799	53.24
70	1,087,786	61.18
85	265,478	67.70
100	68,041	73.19
115	19,596	78.23
130	6,450	82.71

Table 57. Complex Shear Modulus and Phase Angle of the North 17 Percent RAP Binder

N17 RAP		
Temp. (°F)	**G* (Pa)**	**Delta**
41	18,655,893	42.58
55	7,317,072	50.49
70	2,189,465	58.62
85	573,036	65.60
100	142,435	71.55
115	36,974	76.88
130	10,350	81.58

Table 58. Complex Shear Modulus and Phase Angle of the North 30 Percent RAP Binder

N30% RAP		
Temp. (°F)	**G* (Pa)**	**Delta**
41	18,895,283	43.18
55	8,481,259	50.19
70	2,714,123	58.22
85	720,815	65.69
100	174,129	72.25
115	42,622	78.33
130	10,681	83.84

Table 59. Complex Shear Modulus and Phase Angle of the North 50 Percent RAP Binder

50% RAP		
Temp. (°F)	**G* (Pa)**	**Delta**
41	26,644,402	39.52
55	12,462,225	46.43
70	4,101,016	54.76
85	1,107,622	62.74
100	268,850	69.76
115	65,249	76.03
130	16,027	81.61

Table 60. Complex Shear Modulus and Phase Angle of the South 0 Percent RAP Binder

S0 RAP		
Temp. (°F)	**G* (Pa)**	**Delta**
41	20,448,670	43.88
55	6,966,370	51.94
70	1,951,845	58.88
85	503,406	63.46
100	138,183	65.83
115	43,112	67.08
130	15,268	68.38

Table 61. Complex Shear Modulus and Phase Angle of the South 17 Percent RAP Binder

S17 RAP		
Temp. (°F)	**G* (Pa)**	**Delta**
41	29,313,227	40.66
55	11,907,862	48.58
70	4,030,152	55.79
85	1,182,452	61.15
100	327,947	64.56
115	93,057	66.79
130	28,421	68.85

Table 62. Complex Shear Modulus and Phase Angle of the South 26 Percent RAP Binder

S26 RAP		
Temp. (°F)	**G* (Pa)**	**Delta**
41	23,421,238	41.20
55	10,989,958	47.29
70	4,171,332	53.20
85	1,309,267	58.11
100	370,226	61.85
115	103,679	64.99
130	30,565	68.47

Table 63. Complex Shear Modulus and Phase Angle of the South 50 Percent RAP Binder

S50 RAP		
Temp. (°F)	**G* (Pa)**	**Delta**
41	39,303,330	36.51
55	19,057,637	42.94
70	7,396,656	49.50
85	2,338,302	55.53
100	655,688	60.55
115	178,496	64.69
130	50,357	68.88